SAMMAMISH RIVER MODEL VERSION 3

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Introduction

The purpose of this work was to develop a temperature model of the Sammamish River. The Corps of Engineers started this work in 1998. Temperature data was collected in the summer of 1998 along the Sammamish River and the in the main tributaries. In 1999 a temperature model was developed using CE-QUAL-W2 version 2 and calibrated with the data collected during summer of 1998. The work done in 2000 included setting up Version 3 of the model (for its improved river reach modeling capability), calibration with data collected in 1999, recalibration with the 1998 data set, and simulation of six temperature management scenarios. The Corps collected temperature data in the summer of 1999 and hydrologic modeling was undertaken by King County to construct spatially and temporally detailed hydrographs. Version 3 of the model required the redevelopment of a bathymetric grid for CE-QUAL-W2. A FORTRAN program was developed that generates a Version 3 sloped grid directly from a HEC-RAS geometry input file.

Results

The combination of better data sets and a newer version of the model resulted in improved agreement of model output with observations. Average mean errors (AME), a statistical measure of model bias, for the five stations considered ranged from -0.20....C to 0.17....C for the 1999 data set and from -0.14....C to 0.05....C for the 1998 data set. Overall Root Mean Squared errors (RMS) error, the more stringent statistical test, was 0.94....C for the 1998 data set and 0.56....C for the 1999 data set. RMS error based on hourly computed and observed pairs ranged from 0.33....C to 1.12....C. The data sets and model setup are discussed in Section 2 “Model Setup”, the calibration for both 1998 and 1999 are presented in Section 3 “Calibration and Sensitivity Simulations”. Based on the calibration results and a supporting calculation which compared the Railroad Bridge observed temperatures with observed temperatures at the Weir and at Bear Creek, it was concluded that 1998 calibration was limited by the accuracy of the observed flow and temperature data.

The work performed this year included the use of the re-calibrated model for evaluating various management scenarios under a time-series of hypothetical low flow-high temperature conditions for two summer days. The baseline scenario included a 15 cfs surface withdrawal along the Sammamish River. The 6 scenarios involved reduction of the surface withdrawal by 5 cfs, 10cfs, and 15 cfs and three groundwater augmentations (5 cfs, 10 cfs, and 15cfs). There was a small effect caused by reducing the surface withdrawal by 15cfs hence the 5 cfs and 10 cfs reductions were eliminated as being redundant.

The highest examined increase in groundwater inflow (15 cfs) decreased the maximum 2-day temperature in the Sammamish River by 0.7 °C. The 2-day average decreased by 0.5 °C. Eliminating the entire river-wide withdrawal of 15 cfs had no discernible effect on the temperature averaged across the entire river and over the two days of simulation, or on most other temperature statistics. Several recommendations were made for future modeling studies for the Sammamish River system that should be considered prior to any management planning. These include several additional calibration and analysis opportunities, refining of the scenario definitions, extension of

Sammamish River Temperature Study: 1998 and 1999 CE-QUAL-W2 Calibration and Management Scenarios

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1. Summary

This report describes the modeling activities provided under the Scope of Work (SOW) published as Delivery Order No. 004 of Contract # DACW67-00-D-1000 (Seattle District, Corps of Engineers, 2000), by subcontract to Northwest Hydraulic Consultants. The purpose of the SOW is to continue the Sammamish River temperature modeling effort of Martz, et al. (1999) using the model CE-QUAL-W2. This earlier effort was based on Version 2 of the model and calibration data collected during summer of 1998. The activities under the SOW include setting up Version 3 of the model, calibration with data collected in 1999, recalibration with the 1998 data set, and simulation of six temperature management scenarios.

Martz, et al. (1999) noted some limitations in their model calibration, and recommended that additional data be collected, and that sensor locations be improved. They also recommended that Version 3 of the model, which was then under development, be used for its improved river reach modeling capability. Temperature data were subsequently collected in the summer of 1999 by the Corps and hydrologic modeling was undertaken by King County to construct spatially and temporally detailed hydrographs. Version 3, scheduled for public release in late August 2000, was acquired and used in all modeling work included in this report. Not specifically included in the SOW, but necessary to the use of Version 3, was the redevelopment of a bathymetric grid for CE-QUAL-W2. A FORTRAN program was developed that generates a Version 3 sloped grid directly from a HEC-RAS geometry input file.

The combination of better data sets and a newer version of the model resulted in improved agreement of model output with observations. Average mean errors (AME), a statistical measure of model bias, for the five stations considered ranged from -0.20°C to 0.17°C for the 1999 data set and from -0.14°C to 0.05°C for the 1998 data set. Overall Root Mean Squared errors (RMS) error, the more stringent statistical test, was 0.94°C for the 1998 data set and 0.56°C for the 1999 data set. RMS error based on hourly computed and observed pairs ranged from 0.33°C to 1.12°C. The data sets and model setup are discussed in Section 2 “Model Setup”, the calibration for both 1998 and 1999 are presented in Section 3 “Calibration and Sensitivity Simulations”. Based on the calibration results and a supporting calculation which compared the Railroad Bridge observed temperatures with observed temperatures at the Weir and at Bear Creek, it was concluded that 1998 calibration was limited by the accuracy of the observed flow and temperature data.

A further requirement in the Scope of Work was the use of the re-calibrated model for evaluating various management scenarios under a time-series of hypothetical low flow-high temperature conditions for two summer days. The scenario simulations involved three surface withdrawal restoration and three groundwater augmentation scenarios. Some scenarios turned out during simulations to have a small effect that was also well bracketed by results from other scenarios and hence were eliminated as being redundant. Several temperature statistics from scenario simulations are reported in detail in Section 4 “Management Scenarios”. The highest examined (15 cfs) increase in groundwater inflow decreased the maximum 2-day temperature in the Sammamish River by 0.7 °C, and the 2-day average by 0.5 °C. Eliminating the entire river-wide withdrawal of 15 cfs had no discernible effect on the temperature averaged across the entire river and over the two days of simulation, or on most other temperature statistics.

Several recommendations were made for future modeling studies for the Sammamish River system that should be considered prior to any management planning. These include several additional calibration and analysis opportunities, refining of the scenario definitions, extension of

the model into Lake Sammamish, integrating the model with biological effect computations, and model sensitivity studies.

The model and data sets referred to in this report are included on CD-ROM.

2. Model Setup and Data Sets

The model setup began with the Martz et al. (1999) CE-QUAL-W2 Version 2 application to the Sammamish River. Some features of this earlier application were:

- a single branch with irregular segment lengths, a 0.5 m layer thickness, 4 tributaries, and a distributed tributary
- a simulation period of 18 May 1998 to 31 October 1998
- boundary conditions consisting of an upstream flow boundary and a downstream head boundary
- FORTRAN custom modifications include coding to simulate shading by limiting solar radiation[1].

Since better data were collected in 1999, the model was first set up and calibrated for 1999. Detailed investigations were carried out on calibration and sensitivity of the model using this data set and good agreement with observations was obtained.

Following the 1999 calibration, simulations were made with the 1998 input data set and the model parameters used in the 1999 calibration. Acceptable agreement with the 1998 observations was obtained, but was only marginally better than that shown in Martz et al. (1999). Further investigation using model-independent supplemental calculations for both 1998 and 1999 demonstrated that errors in the 1998 calibration were likely due to inaccuracies in the data set, not to any fundamental model failings or model misuse.

2.1 Input Data

There are four data sets available from which to generate model input for simulation of the Sammamish River with CE-QUAL-W2. The four data sets are (1) bathymetric data in the form of HEC-RAS cross-sections; (2) time-varying water surface elevation and inflow rate data; (3) time-varying temperature data; and, (4) time-varying meteorological data.

The bathymetric data were used to create the longitudinal-vertical bathymetric grid. The time-varying elevation and inflow rate data were used as input for the model's hydraulic computations. The time-varying temperature data were segregated into two components. The first component consisted of upstream and tributary inflow temperatures for the model's temperature computations. The second component consisted of instream temperatures used for comparisons to model output. The time-varying meteorological data, observed at Seattle-Tacoma International Airport, were used for the model's surface heat exchange and surface wind shear computations.

Each of the time-varying data sets was available for summer periods in 1998 and 1999. Supporting data sets include the 1998 CE-QUAL-W2 setup files and the scenario specifications in Table 1 and 2 of the Scope of Work. Additional information was provided in Martz et al. (1999) and through telephone conferences and e-mail transmittals.

[1] Shading is now incorporated as an input parameter in Version 3, hence it was not required to make the custom coding changes to the Version 3 source code.

2.2 Bathymetric Data and the CE-QUAL-W2 Grid

A CE-QUAL-W2 grid is composed of longitudinal compartments called segments and vertical compartments called layers. Each segment/layer combination represents a cell. The waterbody bathymetry is represented by setting as inactive the cells that fall below the river bed, and specifying the width for each active cell. The width of a cell represents the width of the waterbody at that elevation and longitudinal location.

Version 3 of CE-QUAL-W2 requires a fundamentally different grid than Version 2 of the model. In Version 2, the grid is horizontal, hence development of the model grid from waterbody bathymetry data requires deciding only the top and bottom elevation of the grid. All cells in a given layer have the same elevation, making elevation of a cell dependent only on its layer index. Version 3 adds a bottom slope term to the hydrodynamic equations and assumes that the entire grid is tilted at this slope. A tilted grid implies that the elevation of any given cell is dependent not only on the layer index, but also on the segment index and the grid slope. Thus, computing the width of any cell from waterbody bathymetry data in Version 3 requires deciding on a grid slope, besides the top and bottom elevation at one end of the grid. Accordingly, a more general method is needed for developing a Version 3 grid than for a Version 2 grid.

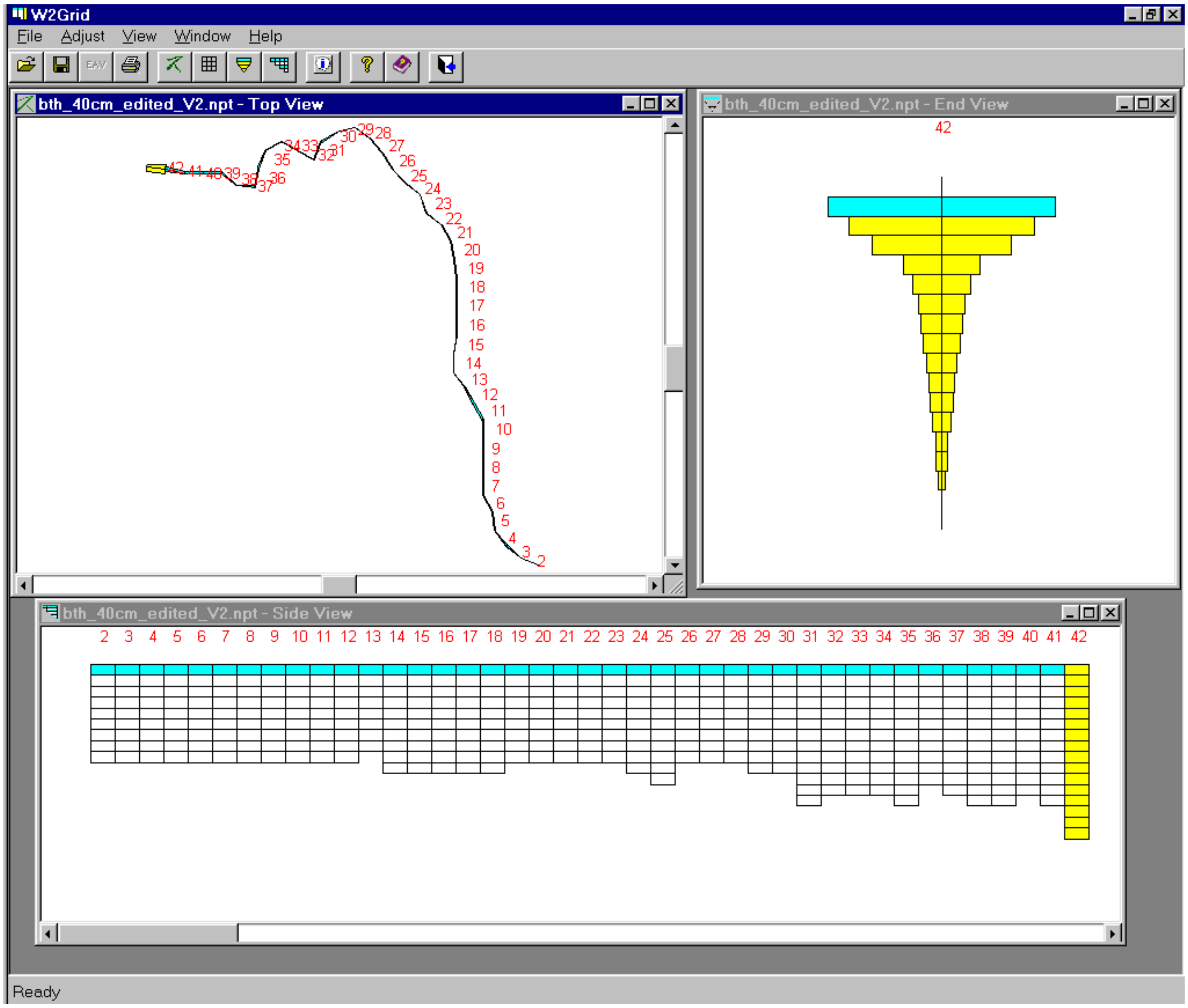
Another incentive for development of a general method to convert HEC-RAS geometry data into a Version 3 CE-QUAL-W2 grid was improvement of grid accuracy beyond that possible with the graphical method used by Martz et al. (1999). Their graphical procedure involved drawing lines of constant elevation on printouts of HEC-RAS cross-sections and reading the widths across the channel (Valentine, pers. comm., 21 June 2000). This procedure could be improved upon by developing a programmed method.

A FORTRAN program was written to convert the HEC-RAS cross-sectional data to a generalized CE-QUAL-W2 Version 3 grid. The approach used was to compute an interpolated channel width at several elevations for each cross-section. To retain maximum information from the HEC-RAS geometry, scanning was done at a high vertical resolution (0.05 to 0.1m) and every cross-section was converted to a CE-QUAL-W2 grid segment. The resultant high resolution grid could be easily processed using W2Studio[2] software into any desired vertical or horizontal resolution. The resulting grid is visualized in Figure 2-1 (next page) as a composite of three orthographic views – looking at the grid from the top, from the side, and looking at the downstream segment alone from the downstream end.

[2] W2Studio is a Graphical User Interface for CE-QUAL-W2, developed and maintained by J. E. Edinger Associates, Inc.

Figure 2-1 CE-QUAL-W2 Version 3 Grid – Orthographic Views

Note that the grid is not horizontal, but sloped. The lower panel image is horizontal as it was generated by importing the Version 3 grid into W2Studio software as if it were a Version 2 grid. W2Studio software is currently compatible only with Version 2 of the CE-QUAL-W2 model.



The HEC-RAS simulation data set includes 290 total cross sections. Of these, 272 cross-sections were converted to W2 segments; the others were unusable cross-sections associated with hydraulic specifications of bridges. For the simulations presented in this report, the adopted grid size was a uniform segment length (Δx) of 500.9 m and a layer thickness (H) of 0.4 m, resulting in a total of 41 segments and 16 layers[3]. The bottom slope of the grid used was set at 0.0687 m km^{-1}. As a comparison, the Martz et al. (1999) grid used a non-uniform segment length (average Δx = 460 m) and a layer thickness of 0.5 m grid for a total of 45 segments and

[3] Note that these values are the active number of segments and layers and that the model grid includes boundary segment and layer padding on either end and would therefore be 43 x 18.

20 layers. The tilt in the grid allows a more economical mapping of a sloped river channel into layers.

The HEC-RAS data set also provides authoritative river mile and landmark information. All observation stations, tributaries and withdrawal locations were mapped onto the grid using the HEC-RAS cross-section documentation.

The profile of the Sammamish River bottom supplied in the HEC-RAS data set is shown in Figure 2-2, with Lake Sammamish on the right and Lake Washington on the left in the figure. Vertical lines represent bridges. The weir at the outlet of Lake Sammamish is shown approximately at channel distance 21000 meters, measured upstream from the Lake Washington boundary.

Figure 2-2 Sammamish River bottom profile from HEC-RAS

Lake Washington is on the left. Vertical lines represent obstructions such as bridges.

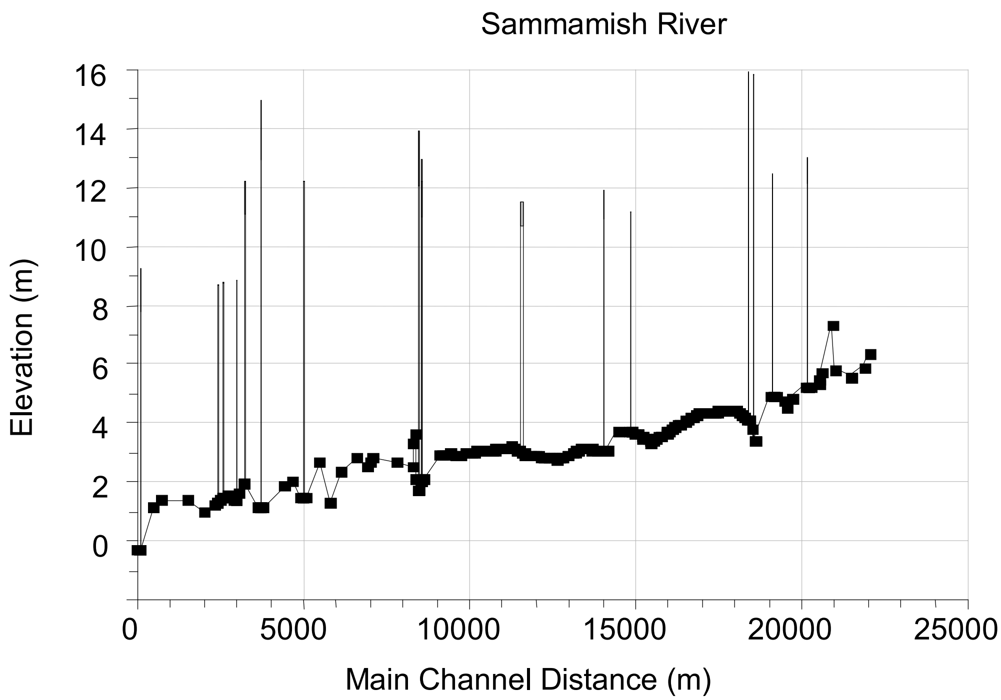


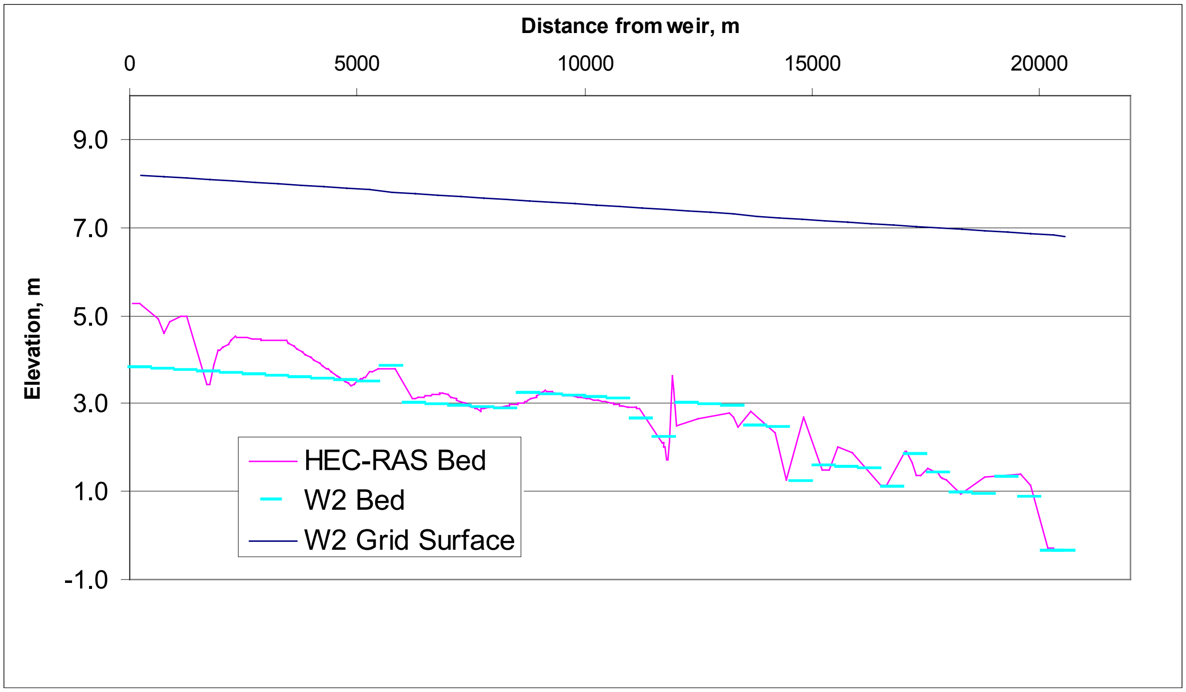
Figure 2-3 illustrates the stream bed shape and the slope used in the CE-QUAL-W2 model grid and the bottom profile derived from the HEC-RAS data set.

The section of Sammamish River modeled in this study consists of the reach from Lake Washington at Kenmore as the downstream end to a point approximately 200 meters downstream of the weir at the outlet of Lake Sammamish as the upstream end. This reach definition avoids the potentially supercritical hydraulic conditions at the weir.

Figure 2-2 and Figure 2-3 show that the CE-QUAL-W2 bathymetry and the HEC-RAS profiles are in agreement with respect to stream bed shape and slope. For further quality assurance that is not documented in this report, the computed widths of CE-QUAL-W2 cells were compared to widths in the HEC-RAS data set. The comparison showed good agreement between the data sets. Good agreement was also observed for cross sectional areas compared graphically at CE-QUAL-W2 segments 9, 14, 19, 24, 29, and 34.

Figure 2-3 Sammamish River bottom profile developed by CE-QUAL-W2 Version 3

Note that "W2 grid surface" is not the assumed or even the likely water surface. It is only the surface of the model grid, displayed here to illustrate the grid slope.



The location of landmarks and points of interest in the Sammamish River, measured downstream from the weir, are shown in Table 2-1. Also shown on this table for reference are the segment numbers of these landmarks from the Version 2 and Version 3 grids. The Railroad Bridge and 132nd St. locations do not appear in the HEC-RAS data set. The 132nd Street location was used as a calibration station only for 1998 simulations.

Table 2-1 HEC-RAS distances, landmarks and corresponding CE-QUAL-W2 segments

Landmark	HEC-RAS distance, m (converted to distances downstream from the weir)	CE-QUAL-W2 Version 2 segment	CE-QUAL-W2 Version 3 segment
Weir	0		
Bear Creek	1478	6	4
Railroad Br.	(n/a)	8	5
116th St. Br.	6072	14	14
124th St. Br.	6876	16	15
132nd St	(n/a)	(n/a)	17
145th St. Br.	9326	21	20
Little Bear Creek	12481	27	26
North Creek	14264	31	29
Blythe Park	17100	39	35
Swamp Creek	20183	45	41
Kenmore Bridge	20901	46	42

2.3 Time-varying Data

The filenames used to develop 1998 time-varying data sets are listed in Table 2-2. The simulation period for 1998, based on the latest starting date and earliest ending date of the model input data, is 2 June 1998 to 9 September 1998. Use of the Weir temperature data set supplied with the 1998 Version 2 setup, however, allowed extension of the simulation period to 29 September 1998. The source of this extended temperature data is not known.

Table 2-2 1998 input and calibration data filenames

Source Filename	Data for model input	Data for model calibration
FINALSAMTEM1998.xls	Hourly water temperatures • Weir (5/18/98 to 9/9/98) • Bear Creek (5/18/98 to 11/29/98) • Little Bear Creek (5/18/98 to 11/29/98) • North Creek (5/18/98 to 11/29/98) • Swamp Creek (5/18/98 to 11/29/98)	Hourly water temperatures • RR Bridge (5/18/98 to 11/29/98) • 116th St. Bridge (5/18/98 to 7/1/1998; 7/13/1998 to 9/9/98) • 132th St. Bridge (5/18/98 to 11/29/98) • 145th St. Bridge (5/18/98 to 11/29/98) • Blythe Park (5/18/98 to 7/30/98)
Full Data Set.xls	• Daily Elevation-Outflow data from Sammamish (6/1/98 to 9/30/98) • Daily Elevations From Kenmore Bridge (6/1/98 to 9/30/98) • Hourly tributary inflows (6/1/98 to 9/30/98)	
Seattle_DATSAV3.txt	• Hourly or more frequent wind direction and speed, sky cover, air and dew point temperatures, station pressure at Sea-Tac (1/1/1991 to 3/31/2000)	

The filenames used to develop 1999 time-varying data sets are listed in Table 2-3. The simulation period for 1999 is June 1 to September 30, based on the latest starting date and earliest ending date of all the model input data.

Table 2-3 1999 input and calibration data filenames

Filename	Data for model input	Data for model calibration
Sammamish temps 1999.xls	Hourly water temperatures • Weir (6/1/99 to 10/22/99) • Bear Creek (6/1/99 to 11/18/99) • Little Bear Creek (6/1/99 to 10/22/99) • North Creek (6/1/99 to 10/22/99) • Kenmore (8/17/99 to 12/22/99) • Swamp Creek (6/1/99 to 10/22/99)	Hourly water temperatures • RR Bridge (6/1/99 to 11/18/99) • 116th St. Bridge (6/1/99 to 11/18/99) • 124th St. Bridge (6/1/99 to 11/18/99) • 145th St. Bridge (6/1/99 to 11/18/99) • Blythe Park (6/1/99 to 11/18/99)
Full Data Set.xls	• Daily elevation-outflow data from Sammamish (6/1/99 to 9/30/99) • Daily elevations at Kenmore Bridge (6/1/99 to 9/30/99) • Hourly tributary inflows (6/1/99 to 9/30/99)	
Seattle_DATSAV3.txt	• Hourly or more frequent wind direction and speed, sky cover, air and dew point temperatures, station pressure at Sea-Tac (1/1/1991 to 3/31/2000)	

2.3.1 Elevation and inflow data for model input

Hydrologic data consist of flow rate and downstream elevation data over the simulation period. Inflow to the Sammamish River from Lake Sammamish was determined from the discharge rating curve of the flow control structure at Lake Sammamish given the elevation (referred to as "the weir"). The inflows in this study were taken as supplied in the file "Full Data Set.xls".

Consistent with the Martz et al. (1999) report, four tributaries are included in the Version 3 application: Bear Creek, Little Bear Creek, North Creek, and Swamp Creek. The flow for Bear Creek is provided by a stream gage maintained by King County. The other three tributary flows were modeled using HSPF and the Everett precipitation station. Local inflow (overland flow and minor tributaries), based on a percentage of flow in Little Bear Creek, was evenly distributed along the length of the river.

Downstream elevation data were obtained from the U.S. Army Corps of Engineers water surface elevation gage located in Lake Washington at Kenmore. The downstream elevation data are required to allow the open boundary condition to freely exchange water depending on changes in Sammamish flow rates and Lake Washington water surface elevations.

Baroclinic flows are a function of the vertical water temperature profiles in Lake Washington and in the lower Sammamish, and are discussed in the sections on "Temperature data for model input" and "Sensitivity to Temperature Profile Data at Kenmore".

2.3.2 Temperature data for model input

The location of each of the temperature sensors for the 1998 data set was described in Appendix A "Temperature Sensor Locations" of Martz et al. (1999) and in Van Rijn (2000) for the 1999 data set. Water temperature data at the Sammamish weir was provided by the Corps. All of the hourly temps supplied were collected by Corps using Optic Stowaways, with some exception. King County daily max/min temps from Lake Sammamish outlet and Bear Creek were used to create hourly temperatures and to replace missing data.

Temperature profiles were measured with similar Optic instrumentation using five sensors placed in the vertical on an anchored cable at nominal depths of 3-, 6-, 9-, 12-, and 15-feet at the head of Lake Washington (Kenmore) for the 1999 data set. Since the profile data are available only after 17 August 1999, the 17 August values were used from the beginning of the simulation.

The sensor locations in 1998 were not entirely satisfactory for measuring tributary temperatures due to the sensors being located primarily in the main stem of the Sammamish rather than in the tributary itself. For example, the North Creek and Swamp Creek sensors were 300 and 100 m downstream of the tributary mouths. The two other tributary sensors (Bear Creek and Little Bear Creek, were located closer (10 and 20 m, respectively) but still in the main channel rather than the tributary itself. The locations were corrected for the 1999 data set.

The water temperature of the distributed inflow is unknown. In the original 1998 simulations, this temperature was taken as equal to the gaged temperature of Little Bear Creek. To generate a more realistic water temperature for the distributed tributaries, a simple water temperature model ("the response temperature") was used. Response temperature is defined as the temperature that a column of fully mixed water would have if surface heat exchange were the only active heat transfer process (i.e., water temperature "responding" only to surface heat exchange). The rate of surface heat exchange can be computed from air and dew point temperature, wind speed, cloud cover, solar radiation, and atmospheric pressure.

The rate of change of response temperature can be written in terms of the net rate of surface heat exchange as

$$D\left(\frac{dT}{dt}\right)=\frac{H_n}{\rho c_p}$$

where

D	=	the mean depth of the water column, m
$\frac{dT}{dt}$	=	the rate of change of water temperature with time, °C s^{-1}
H_n	=	is the net rate of surface heat exchange, W m^{-2}
ρ	=	the density of water, 1000 kg m^{-3}
c_p	=	the specific heat of water at constant pressure, 4186 J kg^{-1} $^{\circ}C^{-1}$

In the above equation, the depth controls thermal storage. For very large depths, the diurnal and seasonal amplitudes are damped. For small depths, diurnal fluctuations are emphasized. For calculating the Sammamish distributed inflow temperatures, a depth of 1 m was assumed because the distributed tributaries have very little thermal storage and react quickly to changes in atmospheric heat sources and sinks.

2.3.3 Temperature data for model calibration

Observed temperature data for model calibration was derived from the same data collection program that provided the input temperatures. Calibration was done using five of these sensors that were located within the river rather than outside the river boundaries.

Some of the time-series temperature data were missing from the records provided or were extremely suspect, and therefore, not used in the calibration. The calibration for 1998 does not include the periods from Julian Day (JD) 182.625 to 194.5 and from 253.417 to 272.0 at the 116th Street Bridge and from JD 212.75 to 272.0 at Blythe Park. For 1999, the calibration does not include the period from JD 238.0 to 272.0 at Blythe Park.

2.3.4 Meteorological data

The parameters of interest for computing surface heat exchange and surface wind dynamics are observed by the National Weather Service station at the Seattle-Tacoma International Airport, located approximately 30 km southwest of the Sammamish River. The observations were supplied by the National Climatic Data Center in DATSAV3 format (NCDC 2000) for the period beginning January 1, 1991 and extending through March 31, 2000. The data are surface observations consisting of wind direction and speed, sky cover, air and dew point temperatures, and station pressure measured at hourly or more frequent intervals. These are the parameters required by CE-QUAL-W2 to compute surface heat exchange and wind surface shear.

Solar radiation is computed internally in the model, but requires cloud cover data to be input. Since 1996, the Seattle-Tacoma International Airport station uses the Automated Surface Observation System (ASOS). The ASOS cloud cover instrument measures sky cover only to

12,000 ft. If there is any cloud cover above 12,000 ft, using the ASOS-derived cloud cover data as model input will estimate solar radiation to be higher than actual radiation.

3. Calibration and Sensitivity Simulations

3.1 Calibration Method

The CE-QUAL-W2 Version 2 application was reported to have certain calibration difficulties when applied to the 1998 data set (Martz et al., 1999):

- computed diurnal amplitudes were smaller than observed
- model error increased in the downstream direction.

Martz et al. (1999) attributed these difficulties to the following model and data limitations:

1. poorly characterized downstream temperature data,
2. uncertain tributary inflow rate and temperature data, and
3. inadequately developed backwater curves.

The first two limitations were addressed by availability of the more detailed 1999 data sets, and the third by using Version 3 of CE-QUAL-W2, which has the specific capability to simulate river reaches.

CE-QUAL-W2 provides two basic types of output: instantaneous snapshots of the longitudinal-vertical distribution of temperature in the Sammamish (synoptic output) and time-varying output at a specific location throughout the simulation period (time series output). For this study, the model time series output routine was modified to write out temperatures for the surface cells corresponding to the locations of the calibration sites (Table 2-1). Several spreadsheets were set up to visualize the model fit and to compute statistics. The procedure was to run the model, plot the computed and observed values against time, and obtain error statistics. The plots were used to establish hypotheses on which any subsequent runs were based, while the error statistics were used as an objective measure of the overall error that must decrease or remain comparable in order to consider a particular simulation as an improvement.

Three types of error statistics were computed. Bias[4] was defined as a simple average of all deviations averaged across time for each station, and then across the stations. Deviations were always defined as predicted minus observed, such that a positive Bias indicates that the model predicts temperatures warmer than observed. Hourly root mean square (RMS) was defined as the root of the sum of squares of the deviations across time for each station. Besides these two standard measures, a daily RMS was defined as the RMS sum of deviations of the daily average predicted from the daily average.

Bias provided a simple estimate of overall bias in the model prediction relative to the observations. The Bias estimate guided decisions on calibration parameters like shading, or extinction coefficients, which tended to produce overall warming or cooling of the model predictions. Because the sign of individual prediction errors does not affect RMS measures,

[4] This measure was originally referred to as average mean error (AME). References to AME may remain in the spreadsheets and documents on the attached CD-ROM, as they preceded the comment requesting that AME be replaced with Bias.

they do not provide an indication of bias, but indicate the extent to which the model failed to replicate the observations. RMS statistics also emphasized the larger errors as errors are squared in the aggregation process. Thus a few large deviations in a time-series could dominate the statistic and mask long periods of accurate predictions. The daily RMS statistic was computed to isolate the model's ability to replicate the diurnal cycle from its ability to replicate the multi-day temperature variations. If the hourly RMS was much larger than the daily RMS, and Bias was low, it was taken to mean that while the model does not replicate the observed temperatures well, the errors cancel out over any single day.

At several points in the calibration process, the model was checked for systematic errors by plotting errors (computed minus observed) against several variables. These included flow, meteorological data (air and dew point temperatures, cloud cover), time of day, and predicted water temperature. If there are systematic errors in the model's ability to capture a process realistically, such plots of residuals usually help identify them.

As noted previously, the model was first set up and calibrated for 1999. Most of the calibration effort was done using this data set. Once acceptable agreement was obtained, the calibration parameter set was applied to the 1998 simulations. Further investigation using model-independent supplemental calculations for 1998 and 1999 demonstrated that calibration errors for 1998 were due to errors in the measured data.

3.2 Calibration Parameters

The main temperature calibration parameters available in CE-QUAL-W2 Version 3 are

- the bottom roughness parameter, Manning's n
- choice of formulations for vertical eddy viscosities
- choice of the transport solution scheme
- the evaporative windspeed formula
- wind sheltering coefficient
- parameters that control the attenuation of solar radiation with depth (β and γ).

Manning's n, a bottom friction parameter, was set to 0.03 based on values reported in the HEC-RAS data set and on the results of calibration simulations.

The horizontal eddy viscosity coefficient, Ax, specifies dispersion of momentum in the x-direction. The horizontal eddy diffusivity coefficient, Dx, specifies dispersion of heat and constituents in the x-direction. Both Ax and Dx are constant over time. The vertical eddy viscosity coefficient, Az, specifies dispersion of momentum in the z-direction. The model computes vertical eddy viscosity implicitly. Four different formulations are available in Version 3. All these formulations were investigated, but no significant differences were found in the results from any of these, hence the default formulation (Nikuradse) was used. The maximum value for eddy viscosity also remained at the default value of 1.0 m^2s^{-1}.

The transport solution scheme used is "Ultimate", a higher-order solution scheme that limits numerical diffusion. The evaporative windspeed function used was that of Brady, Graves, and Geyer (1969).

The wind sheltering coefficient (WSC), with permissible values ranging from 0 to 1, specifies the attenuation of wind relative to the meteorological station value that may occur due to local topography and vegetative cover. A value of 0.75 was used for WSC, based mainly on prior W2 experience but also on calibration investigation with the current application.

The solar radiation attenuation computation is given by the following equation:

$$H_s(z) = (1 - \beta) H_s e^{-\gamma z}$$

where

$H_s(z)$	=	short wave radiation at depth z, W m^{-2}
β	=	fraction absorbed at the water surface
γ	=	extinction coefficient, m^{-1}
H_s	=	short wave radiation reaching the surface, W m^{-2}

For the Sammamish River, β was taken to be 0.55 and γ to be 0.55, values indicative of relatively clear water.

3.3 Calibration Data Quality

Calibration success depends in part on the adequacy of the data sets and the correctness of Version 3 of CE-QUAL-W2, which was undergoing beta testing by the developer during the period of performance of this modeling study. The 1999 data set was very good and generally covered the entire summer simulation period (the exception being the downstream elevation and temperature profile data, which began August 17th, but probably was adequate for calibration purposes – see Section 3.10 “Sensitivity to Temperature Profile Data at Kenmore”). The Sea-Tac ASOS instrumentation only measures cloud cover to 12,000 ft, which could have overestimated solar radiation during periods of significant cloud cover at high elevations.

The poor quality of three calibration sensors was noted by the Corps as comments embedded in the spreadsheets supplied as input data. When the 145th Street temperature sensor was retrieved in 1999, it was completely buried in sediment. When the Blythe Park temperature sensor was retrieved in 1999, it was partially buried and it was in only about 6 inches of water. When the Swamp Creek sensor was retrieved in 1999, it was sitting on the bank. It was suspected that some of the data collected there may have been more indicative of air temperatures rather than water temperatures. The Swamp Creek sensor may have been tampered with because its location was in a heavily used area.

Martz, et al. (1999) noted that the temperature sensors are located near the banks and near the river bed. Therefore, they may not have represented the laterally well-mixed average temperatures that are reported by the model.

3.4 Calibration for 1999

The model was calibrated to generally accepted standards. Time-series plots of model-observed comparisons and other pertinent time series data are shown in Figure 7-1 through Figure 7-7. A statistical summary of the results is shown below in Table 3-1. The statistics are based on residuals taken as computed values minus observed values, hence negative values indicate under-predictions, and positive values over-predictions. It should be recalled that the Bias values tend to be very close to zero, but do so when over-predictions balance under-predictions. The RMS values provide a more stringent statistical test. The values shown in the table indicate an overall error of less than 0.6°C, or 1°F and a negligible bias in the model.

Table 3-1 Error statistics for the 1999 calibration, °C

Station	Hourly/daily average mean error (BIAS)	Hourly root mean squared error (RMS)	Daily RMS
RR Bridge	0.17	0.33	0.24
116th Street	-0.20	0.56	0.34
124th Street	-0.01	0.66	0.30
NE 145th Street	0.11	0.58	0.39
Blythe Park	-0.13	0.61	0.41
Overall	**-0.01**	**0.56**	**0.34**

No discernible relationship was found in the residuals with respect to any of the variables enumerated earlier in Section 3.1. The only generalization that could be made was that residuals are higher in the middle third of the simulation period, and low in the beginning and end. Calibration error also did not appear to be due to a lower than observed diurnal amplitude as in Martz, et al., (1999).

3.5 Application of 1999 Calibration to 1998

The parameters used for 1998 were held identical to those used in the 1999 calibration. Time series plots of model-observed comparisons and other pertinent time series data are shown in Figure 7-8 through Figure 7-14. A statistical summary is shown in Table 3-2.

Table 3-2 Error statistics for the 1998 calibration, °C

Station	Hourly/daily average mean error (BIAS)	Hourly root mean squared error (RMS)	Daily RMS
RR Bridge	-0.04	0.87	0.83
116th Street	0.04	1.12	0.99
132nd Street	0.05	0.98	0.87
NE 145th Street	-0.03	0.97	0.88
Blythe Park	-0.14	0.72	0.65
Overall	**-0.02**	**0.94**	**0.85**

One difficulty with the 1998 calibration data arises because obtaining good results at the downstream stations depends on having obtained good results at the upstream stations. Figure 7-10 shows that there are two periods when the model either over-predicts the observations (early August 1998) or over-predicts the daily minimum values (late August and early September) at the RR Bridge. This discrepancy can be directly tied to errors in the input data sets (see Section 3.6 "Model-independent Data Verification", following). To a certain extent the surface heat exchange processes occurring further downstream tend to correct this initial error, as shown in Figure 7-13 (NE 145th Street) and Figure 7-14 (Blythe Park).

As for 1999, the calibration error did not appear to be due to a lower than observed diurnal amplitude as in Martz, et al. (1999).

3.6 Model-independent Data Verification

The location of the sensor at the RR Bridge (RRB) relative to the sensors at the weir and at the Bear Creek confluence (BC) offers an opportunity to independently verify the model calculations. It is not expected that there will be significant cooling or warming in the short and relatively fast flowing stretch of the river between the weir and BC and then at RRB. If the temperatures that would result from instantaneously mixing the weir inflow and BC inflow compare well to the measured temperatures at RR Bridge, it would verify the flow and temperature data sets at these two locations.

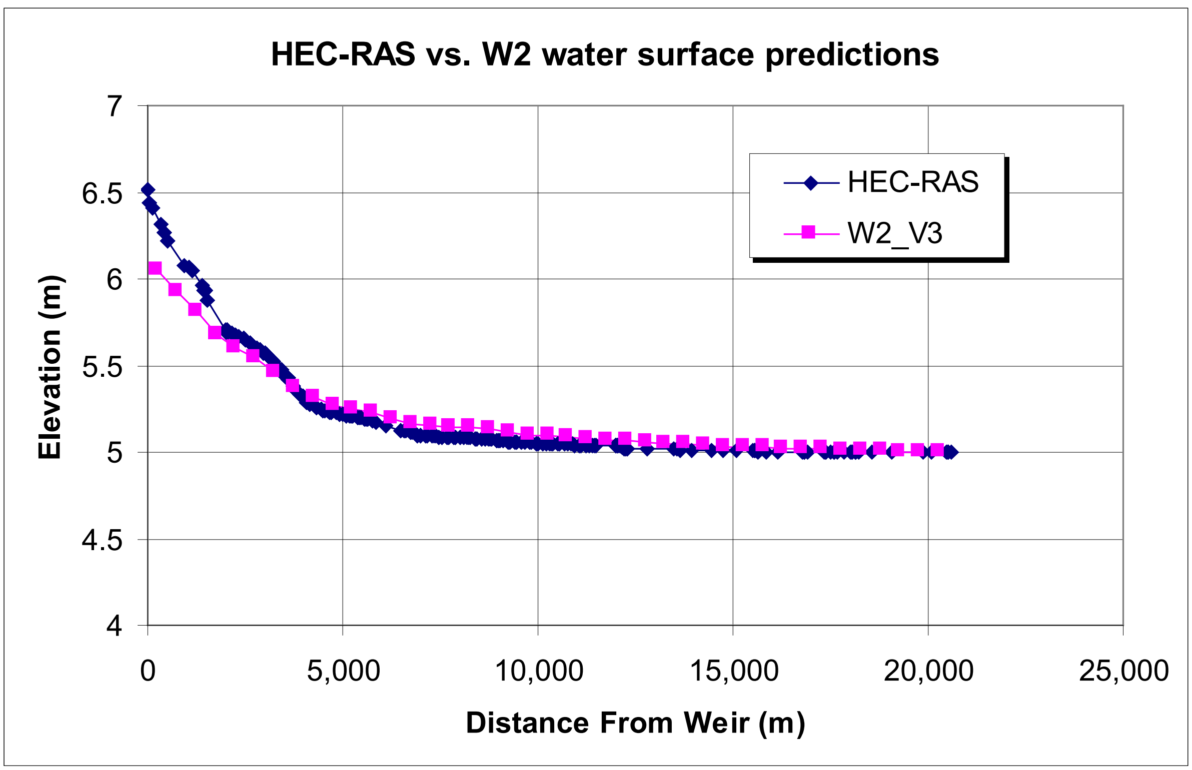
The comparison of well-mixed and observed temperatures for 1999 showed excellent agreement (Figure 7-15 in 7. Appendix A – Large Landscape Format Tables and Figures), but a similar comparison for 1998 did not (Figure 7-16). Furthermore, the nature of this mismatch for 1998 was similar to the mismatch between the 1998 observations and 1998 model predictions at RRB (Figure 7-10). Therefore, it was concluded that the accuracy of the observed flow and temperature data limited the predictive ability of the model for 1998.

3.7 Hydraulic Comparison with HEC-RAS

As another model validation test, the water surface elevations generated by CE-QUAL-W2 were compared to the water surface elevations generated by HEC-RAS to evaluate the hydraulic performance of the model.

The hydraulic condition selected for this comparison is a steady 5 m^3s^{-1} flow rate and a constant 5 m downstream elevation. The CE-QUAL-W2 model, with the bathymetry input data developed for this study, generates water surface elevations that compare well with those generated by HEC-RAS, as shown in Figure 3-1.

Figure 3-1 Comparison of HEC-RAS and W2 steady state water surface predictions



3.8 Sensitivity to Sammamish Lake Outflow Temperature

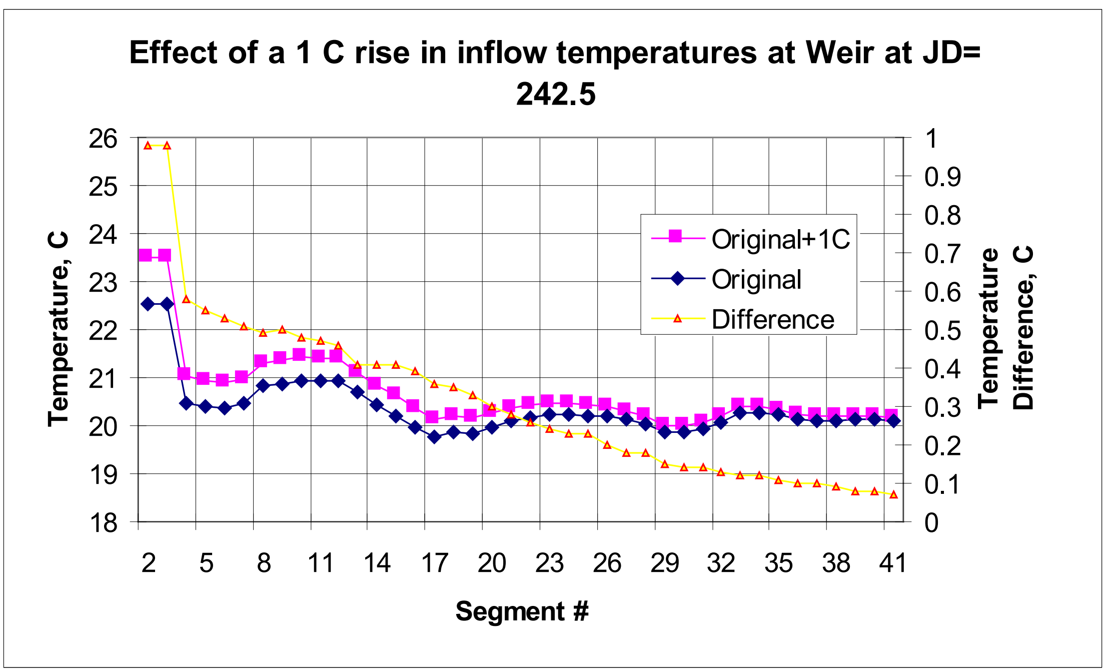
The extent of the impact of changes in Sammamish Lake outflow temperatures will in general depend on the inflow rate, the time of day, and other inflows and meteorological conditions.

For an assessment of how dependent the river temperatures are on the weir inflow temperatures, the model was run with the discharge temperature from Lake Sammamish raised by 1°C throughout the simulation period. Surface heat exchange and mixing with the major and minor tributary inflows were expected to attenuate this temperature rise, but it was not known how rapid this attenuation might be. If attenuation is rapid, Lake Sammamish outflow temperatures may be considered less important to determining Sammamish River temperatures than the downstream flow and heat exchange processes.

Figure 3-2 shows that the downstream attenuation of the introduced 1°C rise is not rapid. The implication is that any systematic uncertainty in Lake Sammamish inflow temperatures remains a significant component of the river model prediction uncertainty, especially in the upstream to middle section of the river. If the weir temperature is uncertain by 1°C, the river temperatures become uncertain by about 0.5°C from just downstream of the confluence with Bear Creek down to segment 13, approximately 6 km downstream of the weir. The uncertainty then attenuates approximately linearly down to around 0.1°C at Kenmore.

Similarly, the model could be used to investigate the impacts of uncertainty in other measured or unmeasured inputs on the stream temperature at any location. The data collection effort could thus be sharply focused to only the important unknown inputs. Monitoring program costs could be reduced by eliminating the measurement of data that does not impact the conclusions required from the model.

Figure 3-2. River-wide mid-day impact of a 1 °C rise in the Lake Sammamish inflow temperature



3.9 Sensitivity to Downstream Bathymetry

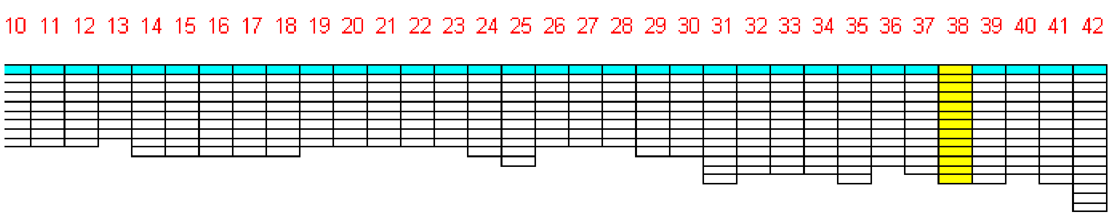
The tasks enumerated in the SOW included an investigation of the sensitivity to downstream bathymetry. This investigation was prompted by concern that recent sediment deposition in the downstream sections of the river may significantly impact the model results. The amount and spatial range of sediment deposition was not specified, and may not be well-known. In any case, for purposes of examining the sensitivity of the model to such a change, a fairly substantial change in the bathymetry was investigated first.

For this purpose, sediment deposition was represented as a filling up of the bottom cells in segments 31-42 of the grid (Figure 3-3). The rationale was that if such a large change does not produce significant differences in the model predictions, then the exact sediment deposition pattern need not be investigated further for purposes of temperature modeling. The two different grid files were used to run 1998 simulations, and the July 27-28 period was examined for differences (Table 3-3)

The comparison of results shows that temperatures at the last segment remained within 0.5°C of the original grid simulation. Temperature difference between the simulations from the two grids reduced to under 0.1°C in the previous segment, which is just 500 m upstream.

Figure 3-3. Grid modification for examination of sensitivity to bathymetry
Note that the grids shown below are sloped, not horizontal. These images show the grid as horizontal because they were generated by importing the Version 3 grid into W2Studio software as if it were a Version 2 grid. W2Studio software is currently compatible only with Version 2 of the CE-QUAL-W2 model.

Downstream end of the original grid



Downstream end of the filled-in grid

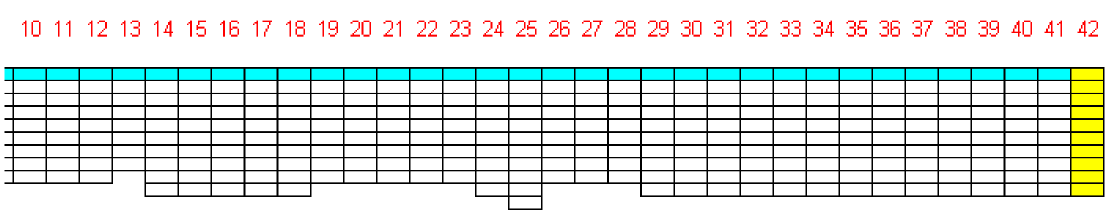


Table 3-3 Model snapshot output from original grid and from "filled-in grid" simulations
Note that temperature is output only at selected segments

Original grid simulation

July 28, 1998 Julian Date = 209 days 15.01 hours Temperature [T1], °C

Layer	Depth	2	4	5	14	17	20	26	29	36	41	42
8	0.66	27.17	25.01	25.05	26.86	26.17	26.06	26.56	26.03	26.40	26.51	26.56
9	0.86	27.10	24.78	24.78	26.19	25.13	24.99	25.61	25.21	25.61	25.75	24.75
10	1.26	27.08	24.55	24.63	25.98	24.71	24.60	25.46	24.85	25.25	24.94	24.40
11	1.66				25.51	24.24			24.33	24.49	24.20	23.87
12	2.06									23.69	23.60	23.43
13	2.46										23.12	23.02
14	2.86										23.05	22.76
15	3.26											22.58
16	3.66											22.50
17	4.06											22.43

"Filled-in grid" simulation

July 28, 1998 Julian Date = 209 days 15.01 hours Temperature [T1], °C

Layer	Depth	2	4	5	14	17	20	26	29	36	41	42
8	0.66	27.17	25.01	25.05	26.83	26.15	26.05	26.60	26.02	26.32	26.43	26.58
9	0.86	27.10	24.78	24.78	26.16	25.11	25.01	25.64	25.20	25.52	25.45	24.96
10	1.26	27.08	24.55	24.63	25.96	24.70	24.63	25.51	24.84	25.28	24.92	24.74
11	1.66				25.48	24.24			24.27	24.96	24.32	24.28

3.10 Sensitivity to Temperature Profile Data at Kenmore[5]

Water temperature measurements at Kenmore serve as the downstream boundary condition of the modeled reach. Beginning 17 August 1999, temperatures were measured with five sensors placed in the vertical on an anchored cable at depths of 3-, 6-, 9-, 12-, and 15-feet. Since boundary condition data prior to this date were needed to maintain a reasonably long simulation period for 1999, it was of interest to determine the sensitivity of model predictions to the downstream boundary temperatures assumed before 17 August 1999. One of the suggestions from Martz et al. (1999) was that uncertainties in downstream boundary temperatures may have been responsible for the calibration becoming poorer going downstream.

The calibrated model was used to run simulations for 1999 with a series of alternative assumptions for the boundary condition data for the missing period. Results using isothermal profiles of 15 C and 30 C (Table 3-4) showed that the effect was limited to the last segment. Since the model grid has a longitudinal spacing of 500 m, it is not correct to infer the upstream extent of the downstream boundary condition effect at any finer resolution than 1 km.

[5] Several simulations were made using the original Martz et al. (1999) Version 2 grid to evaluate the sensitivity of the model to three downstream water temperature profiles: uniform cold (5 C), uniform warm (40 C), and a stratified (10 C – 30 C) profile. The three profiles tabulated in the Draft report version of Table 3-4 showed that the effects on water temperature due to the different boundary profiles did not extend far upstream. Two of the comments received were related to this conclusion. One requested a more explicit conclusion, and the other related to the use of this conclusion in developing data set for the downstream boundary condition. Accordingly, additional sensitivity studies were carried out and reported in this section. The old table and discussion was dropped to avoid redundancy.

Table 3-4 Effect of three distinct downstream temperature boundary conditions

The temperatures at the downstream end of the river profile were captured for the simulation time period of midnight of July 28, 1999. This date was chosen arbitrarily. The caption on each subsection of the table indicates the profile that was assumed for the missing data period of 2 June 1999 through 16 August 1999. The first row of each subsection indicates the index number of each 500 m long segment, segment 42 is the downstream end of the model grid.

Base Case
Boundary condition temperatures (downstream edge) are set to the first available data record on 17 August 1999. Temperatures for this condition are within 22.8 C to 22.6 C from top to bottom

38	39	40	41	42
21.01	21.04	21.13	21.29	21.14
20.44	20.32	20.32	20.59	20.82
20.10	20.04	20.04	20.25	20.70
19.92	19.88	19.88	19.88	20.70
19.80	19.69	19.52	19.41	20.70
19.77	19.31	17.97	17.06	20.70
19.19	18.88		16.19	20.34
				20.33
				20.30
				20.19

15 C isothermal boundary

38	39	40	41	42
21.02	21.04	21.14	21.25	21.30
20.43	20.31	20.28	20.47	20.63
20.09	20.03	20.03	20.19	19.85
19.91	19.87	19.85	19.88	19.85
19.79	19.68	19.48	18.90	19.85
19.76	19.30	17.93	16.66	19.85
19.18	18.87		16.23	19.35
				19.27
				19.21
				19.15

30 C isothermal boundary

38	39	40	41	42
21.00	21.03	21.13	21.25	20.80
20.44	20.32	20.31	20.47	20.76
20.11	20.05	20.05	20.20	20.74
19.93	19.89	19.88	19.88	20.74
19.81	19.70	19.50	19.45	20.74
19.78	19.31	17.96	17.14	20.74
19.20	18.89		16.18	20.71
				20.71
				20.71
				20.72

The sensitivity analysis clearly demonstrates that downstream temperature profile data has almost no impact on the temperature in the Sammamish River.

4. Management Scenarios

4.1 Setup of Base Case and Scenarios

The Base Case and Scenarios specifications were developed from the SOW, especially the section on “Modeling” and the boundary condition data in Table 1 and 2 of the SOW, and from a subsequent inquiry (Jain and Buchak, 2000) and clarification (Barton, 2000). The following is a key excerpt from the SOW regarding the specifications of the Base Case.

> *The base scenario shall be representative of the warmest stream temperatures and lowest flows at a location downstream of the confluence of Bear Creek (based on 1998 and 1999 data). This scenario will assume that 15.0 cfs of surface water is withdrawn between the Bear Creek confluence and the I-405 crossing. Withdrawals will be represented as continuous or as a series of 10 evenly distributed points along the reach. For base case flows see table 1 and for base case temperatures see table 2.*

Surface restoration scenarios reduced the surface water withdrawals from 15 cfs to 10 cfs, 5 cfs or 0 cfs. Segments 4 through 28 span the section from Bear Creek confluence through I-405 crossing. Further, since the segments are equal in length, a withdrawal flow file was set up with 25 withdrawals, one in each segment, and each assigned 1/25th of the total withdrawal flow defined for each scenario.

Groundwater augmentation scenarios added groundwater inflow of 5 cfs, 10 cfs, and 15 cfs. These scenarios were implemented by adding the three specified levels of additional flow to the existing distributed inflow file. The temperatures for the so augmented inflow were computed by flow-weighting the Base Case distributed inflow temperature with the specified groundwater temperature of 13 C.

Scenarios were run using 1998 conditions wherever the required inputs were incompletely specified in the SOW. This choice was intended to reflect the Corps' emphasis on the 27-28 July 1998 period. The model was run from 19 July onwards to allow enough simulation "spin-up" time to eliminate the effect of initial conditions. The boundary data used for 19-26 July was either derived from the 1998 historical record, or from the conditions specified for 27-28 July, as appropriate, and not necessarily exactly as proposed in Jain and Buchak (2000). One of the objectives in setting up the base case and scenarios was avoidance of large transients starting the midnight of 27 July that might hide the true effect of the restoration scenarios. For example, the withdrawal and distributed inflows used for the spin-up period were as specified for the 27-28 July period, but to avoid unrealistic warming of the river prior to the period of investigation, the meteorological data, inflow temperatures and bulk inflows were compared to whatever was estimated for those dates for the 1998 calibration simulations. Estimated distributed inflow during 19-27 July 1998 ranged from 0.26-0.28 m^3s^{-1}, which compared well with the 0.164 m^3s^{-1} (1.7 x Bear Creek specified flow) that was used in the Base Case and Scenarios for this period.

Note that the SOW specified that groundwater be represented as a distributed inflow, and that specification was followed in the scenario setups reported here. However, examination of the CE-QUAL-W2 source code revealed that distributed inflow is always added to the top layer alone and is allocated to each segment in proportion to its surface area relative to the branch surface area for the current top layer. While this is correct for precipitation, and perhaps acceptable for runoff and minor tributaries, it does not appear correct for groundwater inflows. Groundwater inflows should largely occur in the bottom layer, and as a first approximation be proportional to the percent of river-bed area that is exposed to a given layer in the model.

The input filenames and files modified to set up the Base Case and various scenarios are summarized in Table 7-1.

4.2 Scenario Visualization

Base case and scenario simulations were visualized in three ways:

1. using a longitudinal temperature profile of surface temperatures

2. using river-wide surface maximum and river-wide surface average temperatures
3. summary of the spatial and temporal displays in matrix form

The term, “surface temperature” in the following discussion refers to the model temperature prediction for the surface layer. Layers in the current model grid are nominally 0.4 m thick. The surface layer may be thicker or thinner than the formal layer thickness, as the model figures out the lowest surface layer index in the entire waterbody, and computes surface layer thickness in each segment relative to the top of that layer index. When the excess surface elevation of the lowest elevation increases (decreases) to a preset fraction of the next higher (lower) layer, a new layer is added (subtracted) and the excess elevations are recomputed. In situations where the waterbody shows a wide range of water surface elevations relative to the slope of the grid, the “surface” layer thickness at some waterbody locations may even span several layers’ worth of depth.

The effect of the restoration scenarios along the river was examined using a longitudinal temperature profile of surface temperatures. The effect was expected to vary with time, hence the 2-day maximum and the 2-day average temperature for the duration of two diurnal cycles of 27-28 July 1998, was examined. This approach is consistent with the analysis in Martz et al. (1999). Two specific points in time, close to the maximum and minimum temperature occurrences, were also selected for illustration of actual snapshots of the river, as temporal aggregation may miss some important effects seen only at instants in time.

The SOW also requested information on the hourly variation of the effects of the scenarios examined. Since maximum river temperatures are achieved at slightly different times of day at different river locations, hourly variation of the scenario effects was examined using river-wide surface maximum and river-wide surface average temperatures. The minimum temperature was of interest to determine how refuge temperatures at the surface are affected in any of the restoration scenarios. In addition to the three spatially aggregated measures, Segment 20, near the 145th Street Bridge, was examined to capture the actual snapshots of the river at the middle section of the river. Analogous to the selection of specific time slots for display, specific segments were selected for display so that spatial aggregation did not hide trends that occured at a specific location.

Finally, a table was prepared for each Scenario that displayed in matrix form, the plotted spatial and temporal aggregates of the model Scenario predictions. This table included the 2-day maximum and 2-day average of the river-wide average, maximum and minimum temperatures besides the time and space slots that were selected for plotting. Statistics at segments 10 and 30, although not plotted for clarity of the figures, were included in this table to show longitudinal variation in the results.

As per the author’s suggestion in the draft report and the approval of the Corps and King County reviewers, this work examined and documented only the extreme scenarios, i.e. the 15 cfs surface restoration (SR3), and the 5 and 15 cfs groundwater augmentation (GA1 and GA3). Since SR3 did not show significant effects, SR2 and SR1 were not investigated. However, since GA3 demonstrated discernible effects, therefore GA1 was also investigated and included in this report. The scenarios not included in this report are expected to demonstrate effects that are well-bracketed within one or more of the scenarios included in this report, and therefore may be considered redundant information.

4.3 Base Case

The Base Case results are important for understanding and placing in perspective the effects of the restoration scenarios. Hourly plots showed that the envelope of stream-wide maximum and minimum temperatures is regular and sinusoidal, but time-series at individual locations showed a pattern that, while predominantly sinusoidal, was not as regular.

Similarly, the longitudinal profiles showed that temporal minimum and maximum temperatures do not always occur at the same time in all locations. Longitudinal profiles clearly showed a sharp drop of temperature at the confluence with Bear Creek at all hours. The diurnal maximum temperatures then rose slowly downstream, but the diurnal minimum temperatures continued to fall for some distance downstream and then rose relatively sharply. However, around approximately 7-8 km from the weir the diurnal maximum and minimum both reached a local peak. There was another sharp drop at 12 and 13.5 km respectively, and relatively steady temperatures thereafter. Maximum diurnal fluctuations appear to occur around 6 km from the weir.

4.4 Comparison of Scenarios

The Base Case and SR3 showed very little difference in the aggregate measures. The maximum temperatures actually increased slightly with decreased surface withdrawal. This effect was possibly due to the surface-biased withdrawals in the Base Case taking net heat away from the river, exposing cooler water from below the surface.

In the original Version 2 of the model, W2 “withdrawals”, i.e. lateral withdrawals, simply specified the outflow from a layer or a contiguous range of layers. In Version 3 of the model, lateral withdrawals have been updated to use the selective withdrawal algorithm. This algorithm determines layer-specific flows given the withdrawal structure elevation and the current vertical density structure. To help insure that this recently introduced algorithm worked correctly, the Base Case was run in another way, i.e. with distributed inflows set to a negative value (0.164-0.425 m^3s^{-1}= -0.261 m^3s^{-1}), and withdrawal flows set to zero. This interpretation of the Base Case had the same water balance, but a different heat balance, as the distributed inflow set to zero cannot in general be at the same temperature as the withdrawal outflow that it compensated for. However, the interpretation is close because the distributed inflow temperatures were comparable to river surface temperatures at the time of year examined. The results indeed showed agreement within 0.1 °C, confirming that withdrawal calculations are probably not grossly incorrect.

The withdrawal-free definition of the Base Case being identical to the withdrawal+distributed inflow Base Case also confirmed that increasing or reallocating the surface layer inflows and outflows by 15 cfs was in itself not an important influence on the river temperatures, unless accompanied by large temperature differences between original and new flows. The three simulations with such flow manipulations (Base Case, Base Case as no withdrawals and negative distributed flow, and SR3) did not show any significant differences as the temperatures of all the flows involved are comparable. The GA3 scenario, while representing a similar 15 cfs alteration of flow balance, showed larger changes to the river temperature because groundwater temperature used (13 C) was substantially cooler than the river at the time of the year examined.

The SR3 effects were more pronounced at some locations in the river than others, and even reversed direction at some locations. Minimum temperatures decreased under SR3 wherever maximum temperatures increased, suggesting that the major effect of the SR3 is to dampen the diurnal cycle at some locations and to enhance it at others.

Groundwater augmentation cooled the river, as expected from the addition of a 13 C inflow to warm surface waters. The effect ranged from about 0.3 to 0.4 °C at segment 10 to about 1.0 °C at segment 20 and 30. The similarity of the effect at segment 20 and 30 computed from the information in Tables 4-1 and Table 4-4, as well as an examination of the longitudinal plots in Figures 7-25 and 7-26, suggested that the cooling effect does not continue to increase beyond approximately 1 °C as the river water travels downstream.

Table 4-1 Hourly-longitudinal temperature matrix for the Base Case

	Average over all segments	Maximum over all segments	Minimum over all segments	Segment 10	Segment 20	Segment 30
2-day maximum through time	27.0	28.0	25.6	27.3	28.0	26.1
2-day average	24.9	26.0	23.7	24.4	25.3	24.5
2-day minimum through time	22.7	23.9	21.6	21.7	22.9	23.1
7/27/98 18:01	26.6	27.9	25.5	26.8	27.0	25.8
7/28/98 6:00	23.6	24.6	22.1	22.2	23.9	23.3

Table 4-2 Hourly-longitudinal temperature matrix for SR3

	Average over all segments	Maximum over all segments	Minimum over all segments	Segment 10	Segment 20	Segment 30
2-day maximum through time	27.0	28.4	25.6	27.5	27.5	26.4
2-day average	24.9	26.1	23.7	24.4	25.2	24.6
2-day minimum through time	22.6	23.9	21.5	21.5	23.1	22.8
7/27/98 18:01	26.6	28.3	25.6	26.7	26.4	25.8
7/28/98 6:00	23.6	24.7	22.0	22.1	24.5	23.4

Table 4-3 Hourly-longitudinal temperature matrix for GA1

	Average over all segments	Maximum over all segments	Minimum over all segments	Segment 10	Segment 20	Segment 30
2-day maximum through time	26.7	27.8	25.6	27.2	27.6	25.8
2-day average	24.6	25.8	23.6	24.3	25.0	24.2
2-day minimum through time	22.4	23.9	21.5	21.6	22.7	22.7
7/27/98 18:01	26.3	27.6	25.3	26.7	26.6	25.5
7/28/98 6:00	23.3	24.2	22.0	22.1	23.6	22.9

Table 4-4 Hourly-longitudinal temperature matrix for GA3

	Average over all segments	Maximum over all segments	Minimum over all segments	Segment 10	Segment 20	Segment 30
2-day maximum through time	26.1	27.3	25.2	26.9	26.8	25.2
2-day average	24.2	25.6	23.3	24.1	24.3	23.6
2-day minimum through time	22.1	23.9	21.2	21.5	22.3	22.1
7/27/98 18:01	25.8	27.1	24.8	26.4	25.8	24.9
7/28/98 6:00	22.9	23.9	21.9	22.0	23.1	22.4

5. Recommendations for Further Work

The modeling study identified several directions for further work. These are discussed below.

5.1 Additional Calibration and Analyses

Version 3 of the model allows for segment-specific shading parameters. These parameters were not used in the calibration. Estimates of canopy cover from a field survey could further improve the model calibration as temperatures in this system have been shown to be sensitive to shading (Martz et al., 1999).

Extinction of radiation at the surface and within the water column is described in the model with two parameters, both of which were varied to achieve calibration. Field measurements or anecdotal information on water clarity such as Secchi depths will be helpful to check these calibration parameters. It is possible that clarity varies with season, possibly dependent on the growth of algal species.

Calibration of the modeled diurnal – longitudinal dynamics to intensive infra-red measurements, which we understand may be available for some dates, will probably lead to substantial insights into the river dynamics.

Tracer simulations with the model will similarly be an additional source of insight. A numerical tracer can be easily introduced at the upstream or downstream end, to any of the tributaries, to the distributed tributary, or injected into any model cell at any point in time. The model can then display the distribution of the tracer at any instant at all segments, i.e. snapshots, and at any location through time.

5.2 Refinement of Definition of Base Case and Scenarios

The flow and temperature conditions specified in the scenarios are essentially a selected, steady-state subset of many possible combinations of time-varying flow and temperature regimes. However, a statistically more correct approach would be to use the model for a ten year simulation using naturally-occurring combinations of flow and temperature. Such a simulation would yield long-term time series of temperature at any location along the Sammamish for comparison to similar time series for the Base Case. These time series results would be presented in statistical form, as tables showing the number of days extreme temperatures would be exceeded. The advantage of this approach is these statistics would directly incorporate all combinations of flow and temperature that would have occurred over the past ten years. CE-QUAL-W2 has been run in previous cases in this mode (e.g., Buchak, et al., 1991; Buchak et al., 1996). This approach has also been used with other models (Jain et al., 1998). This approach would mesh well with the HSPF modeling, which is normally done on the basis of multi-year simulations (see, for example, Jarrett, 2000).

Data for such a ten year simulation is either available or can be generated. Flows can be directly computed by HSPF[6], the meteorological data for Sea-Tac has already been acquired, and the temperature data for the tributaries can be estimated using the response temperature approach. However, CE-QUAL-W2 would need to be extended into Lake Sammamish.

[6] For the ten year simulations, use can be made of an interface between HSPF and CE-QUAL-W2 (Jarrett et al., 2000).

5.3 Extension of the Model into Lake Sammamish

It is strongly recommended that the model be extended to include Lake Sammamish.

In extending the model upstream into the lake, the questions raised in Martz et al. (1999) with respect to the availability of cold water from Lake Sammamish could also be answered. These questions have to do with 1) the performance of any release structure in accessing bottom colder water, likely easily modeled with existing algorithms in the code, and 2) the possibility of depleting the cold water reserve prior to the end of the summer, also easily examined with simulation scenarios using different hypolimnetic pumping rates and pump locations.

A comment received on the draft version of this report noted that Lake Sammamish "has a problem with low dissolved oxygen (DO) in the hypolimnion leading to phosphorus loading leading to intense algal blooms and subsequent poor water quality". Extending the model into Lake Sammamish will also allow addressing this problem. CE-QUAL-W2 can model the changes in vertical mixing and reaeration in the lake, and thus possible improvements in bottom DO, that might occur from withdrawal. CE-QUAL-W2 also models the water quality and transport processes that are likely necessary for investigating DO in Lake Sammamish.

5.4 Biothermal Computations

With ten year's worth of time series input data and temperature predictions, additional detailed and scientifically rigorous computations (Jain et al., 1998) could be carried out that estimate biological effects due to temperature changes. These computations would be based on the considerable literature on bioenergetic models for various fish species. Bioenergetic modeling can be carried out at several levels of detail, hence it should be possible to match the model sophistication to the level of availability of species-specific data. Coupling the stream temperature models with bioenergetic based models can directly provide impacts on a selected index of biological health, that can include growth potential, feeding potential, mortality risk at different life stages, reproductive failure risk, or even actual growth estimates.

5.5 Sensitivity Studies

With two years of data and a reasonably calibrated model, it is possible to establish with a high degree of accuracy which measured inputs have the most impact on the river temperatures. This approach can help refine the field program while keeping costs the same or lower. For instance, sensitivity studies revealed that intensive downstream temperature monitoring is not required to assess upstream temperatures. These sensors could be located elsewhere in the river to help improve model calibration.

Perhaps more importantly, using the model in this "research mode" also enables assessing the likely importance of the hypothesized but unmeasured and difficult to measure inputs like the groundwater inflow/outflow effect, bed heat exchange, seasonal variations in water clarity, wind sheltering, stream shading, and bottom roughness.

6. References

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7. Appendix A – Large Landscape Format Tables and Figures

Table 7-1 Base Case and Scenario setup summary

Boundary data	BASE	SR1	SR2	SR3	GA1	GA2	GA3
File							
QIN	QIN_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
QTR1	QTR1_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
QTR2	QTR2_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
QTR3	QTR3_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
QTR4	QTR4_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
QDT	TBD	Base Case	Base Case	Base Case	qdt_ga1.npt	qdt_ga2.npt	qdt_ga3.npt
EDH	edh_br1.npt from 1998	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
TIN	Tin_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
TTR1	TTR1_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
TTR2	TTR2_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
TTR3	TTR3_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
TTR4	TTR4_base.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
TDT	TIN_1m_1998.np t	Base Case	Base Case	Base Case	tdt_ga1.prn	not constructed	tdt_ga3.prn
TDH	tdh_br1.npt from 1998	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
met.npt	met_1998.npt	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case
QWD	qwd_base.npt 25 withdrawals	qwd_sr1.pr n	qwd_sr2.prn	qwd_sr3.prn	Base Case	Base Case	Base Case

Table 7-2 Snapshot output from Steady State simulations with CE-QUAL-W2.

```
CE-QUAL-W2 V3.0, April, 1995
Sammamish
version 3 test run
low slope grid - 18 layers
deepened and smoothened grid, min B=2.0m, I=2 thru 9 down to k=10


Model run at 14:45:44 on 03-JUL-00

Time Parameters
---- ----------

  Gregorian date      [GDAY] =         September 20, 1999
  Julian date         [JDAY] =       263 days 12.01 hours
  Elapsed time      [ELTMJD] =       110 days 12.01 hours
  Timestep             [DLT] =        60 sec
    at location  [KLOC,ILOC] = (  1,  1)
  Minimum timestep  [MINDLT] =         4 sec
    at Julian day    [JDMIN] =       155 days  0.98 hours
    at location  [KMIN,IMIN] = (  0,  0)
  Limiting timestep
    at location  [KLIM,ILIM] = (  1,  1)
  Average timestep   [DLTAV] =        58 sec
  Number of iterations [NIT] =    163039
  Number of violations  [NV] =         0

Meteorlogical Parameters
------------- ----------

  Input
    Air temperature       [TAIR] =    22.78 øC
    Dewpoint temperature  [TDEW] =    12.80 øC
    Wind speed            [WIND] =     3.59 m/sec
    Wind direction         [PHI] =     5.10 rad
    Wind sheltering        [WSC] =     0.85
    Cloud cover          [CLOUD] =     0.00
  Calculated
    Equilibrium temperature [ET] =     0.00 øC
    Surface heat exchange [CSHE] = 0.00E+00 m/sec
    Short wave radiation   [SRO] = 1.39E-04 øC m/sec

Inflows
-------

  Upstream inflows
    Branch  1
      Layer       [KQIN] =    6-10
      Inflow       [QIN] =    5.00 m^3/sec
      Temperature  [TIN] =   20.30 øC

  Distributed Tributaries
    Branch  1
      Inflow      [QDTR] =    0.00 m^3/sec
      Temperature [TDTR] =   13.33 øC


  Tributaries
    Segment     [ITR] =       4      26      29      41

    Layer       [KTR] =   10-10   10-10   11-11   14-14

    Inflow      [QTR] =     0.0     0.0     0.0     0.0
```

```
    Temperature [TTR] =    14.0    13.3    14.4    13.3
Outflows
________
Surface Calculations
_______ ____________

  Evaporation [EV]
  ___________

    Branch  1 =    0.00
External head boundary elevations
________ ____ ________ __________

  Branch  1
    Downstream elevation [ELDH] =   5.000 m
Geometry
________

  Surface layer   [KT] =        6
  Elevation (m) [ELKT] =    5.002

  Current upstream segment [CUS]
  _______ ________ _______

    Branch   1 =   2
                                   &l1o4e4.8C&a8L
                                                                             Water Surface, m
                                                                             _____ _______

     2       3       4       5       6       7       8       9       10      11      12      13      14      15      16
    6.05    5.93    5.81    5.68    5.60    5.54    5.46    5.37    5.31    5.28    5.25    5.23    5.19    5.17    5.15
```

Sammamish
version 3 test run
low slope grid - 18 layers
deepened and smoothened grid, min B=2.0m, I=2 thru 9 down to k=10

Model run at 14:45:44 on 03-JUL-00

September 20, 1999 Julian Date = 263 days 12.01 hours Timestep violations [NVIOL]

Layer	Depth	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6	0.50	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	0.70	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
8	1.10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
9	1.50	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
10	1.90	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		0.	0.
11	2.30													0.	0.
12	2.70														
13	3.10														
14	3.50														
15	3.90														
16	4.30														
17	4.70														

September 20, 1999 Julian Date = 263 days 12.01 hours Horizontal velocity [U], m/s

Layer	Depth	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6	0.50	4.4E-01	4.2E-01	4.5E-01	3.8E-01	3.5E-01	3.7E-01	3.7E-01	3.5E-01	2.9E-01	2.5E-01	2.8E-01	3.2E-01	2.9E-01	2.1E-01
7	0.70	4.4E-01	4.3E-01	4.7E-01	3.7E-01	3.3E-01	3.5E-01	3.5E-01	3.4E-01	2.8E-01	2.4E-01	2.7E-01	3.1E-01	2.8E-01	2.0E-01
8	1.10	4.3E-01	4.1E-01	4.5E-01	3.5E-01	3.1E-01	3.4E-01	3.4E-01	3.1E-01	2.6E-01	2.2E-01	2.4E-01	2.8E-01	2.6E-01	1.9E-01
9	1.50	4.0E-01	3.8E-01	4.1E-01	3.2E-01	2.9E-01	3.2E-01	3.3E-01	2.9E-01	2.3E-01	1.9E-01	2.2E-01	2.4E-01	2.4E-01	1.7E-01
10	1.90	3.2E-01	3.0E-01	3.3E-01	2.6E-01	2.2E-01	2.5E-01	2.6E-01	2.3E-01	1.9E-01	1.6E-01	0.0E+00		2.1E-01	1.5E-01
11	2.30													1.7E-01	1.2E-01
12	2.70														
13	3.10														
14	3.50														
15	3.90														
16	4.30														
17	4.70														

September 20, 1999 Julian Date = 263 days 12.01 hours Vertical velocity [W], m/ s

Layer	Depth	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6	0.50	2.5E-06	3.4E-05	9.9E-05	9.7E-05	-1.3E-06	-1.3E-05	2.3E-05	5.4E-05	4.6E-05	2.2E-06	-6.6E-06	-2.7E-06	1.8E-05	3.8E-06
7	0.70	-6.7E-05	4.3E-05	1.1E-04	2.5E-05	-4.9E-05	-6.6E-05	1.3E-05	1.1E-04	1.0E-04	7.5E-06	-1.8E-05	-7.0E-07	6.7E-05	2.2E-05
8	1.10	-2.1E-04	-2.1E-05	9.6E-05	-5.7E-05	-4.8E-05	6.7E-06	1.1E-05	5.8E-05	8.4E-05	1.2E-05	-3.8E-05	-3.3E-07	1.3E-04	3.1E-05
9	1.50	-1.4E-04	-1.5E-05	2.2E-05	-4.5E-05	-2.4E-05	2.3E-05	7.0E-06	-2.3E-05	5.5E-06	-3.8E-06	-5.9E-05	0.0E+00	2.0E-04	1.8E-05
10	1.90	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00		9.7E-05	-1.7E-05
11	2.30													0.0E+00	0.0E+00
12	2.70														
13	3.10														
14	3.50														
15	3.90														
16	4.30														
17	4.70														

```
Sammamish
version 3 test run
low slope grid - 18 layers
deepened and smoothened grid, min B=2.0m, I=2 thru 9 down to k=10


Model run at 14:45:44 on 03-JUL-00


September 20, 1999       Julian Date =   263 days 12.01 hours                    Temperature [T1], <o/>C

Layer  Depth       2        3        4        5        6        7        8        9       10       11       12       13       14       15
   6    0.50   20.28    20.17    20.08    20.03    19.94    19.89    19.87    19.85    19.83    19.76    19.66    19.59    19.55    19.55
   7    0.70   20.25    20.15    20.07    20.00    19.92    19.87    19.85    19.83    19.80    19.72    19.63    19.57    19.52    19.50
   8    1.10   20.25    20.13    20.04    19.98    19.90    19.85    19.82    19.82    19.78    19.69    19.60    19.56    19.51    19.47
   9    1.50   20.24    20.12    20.02    19.95    19.88    19.83    19.78    19.78    19.76    19.67    19.56    19.54    19.49    19.45
  10    1.90   20.23    20.09    19.99    19.91    19.85    19.80    19.75    19.73    19.72    19.63    19.53             19.47    19.43
  11    2.30                                                                                                            19.43    19.39
  12    2.70
  13    3.10
  14    3.50
  15    3.90
  16    4.30
  17    4.70

September 20, 1999       Julian Date =   263 days 12.01 hours             Vertical eddy viscosity [AZ], m^2/s

Layer  Depth       2        3        4        5        6        7        8        9       10       11       12       13       14       15
   6    0.50 4.1E-04 2.6E-03 3.4E-03 1.1E-03 4.1E-03 4.6E-03 4.0E-03 2.5E-03 7.0E-04 9.3E-04 1.4E-03 2.4E-03 6.6E-04 6.2E-04
   7    0.70 2.0E-03 4.2E-03 2.7E-03 3.9E-03 3.6E-03 1.7E-03 1.1E-03 3.2E-03 3.0E-03 2.5E-03 2.4E-03 4.1E-03 3.5E-03 2.2E-03
   8    1.10 2.3E-03 2.5E-03 3.5E-03 2.6E-03 2.2E-03 1.5E-03 8.2E-04 2.3E-03 3.0E-03 2.6E-03 1.6E-03 3.8E-03 3.8E-03 2.7E-03
   9    1.50 3.6E-03 3.5E-03 3.5E-03 2.7E-03 2.5E-03 2.7E-03 2.7E-03 2.3E-03 1.6E-03 1.3E-03 0.0E+00 0.0E+00 3.3E-03 2.5E-03
  10    1.90 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00 0.0E+00         1.8E-03 1.1E-03
  11    2.30                                                                                                         0.0E+00 0.0E+00
  12    2.70
  13    3.10
  14    3.50
  15    3.90
  16    4.30
  17    4.70
                                     E&l6.0c7E(s0p16.67h8.5v0s0b0T(10U&a8L

************* Subtract layer  6 at Julian day =  267.958 NIT =  169627************



**************  Normal termination at 14:57:53 on 03-JUL-00     ****************


Runtime statistics
  Grid = 43 x 18
    Maximum active cells =  258
    Minimum active cells =  217
    Segment lengths        500.9 -   500.9 m
    Layer heights           0.40 -    0.40 m
  Timestep
    Total iterations      177054
    # of violations            0
    % violations             0.0
    Average timestep          58 sec
    Simulation time          120 days  0.01 hours
  Total runtime =    12.16 min
```

Figure 7-1 1999 Sammamish River inflow and tributary inflow timeseries

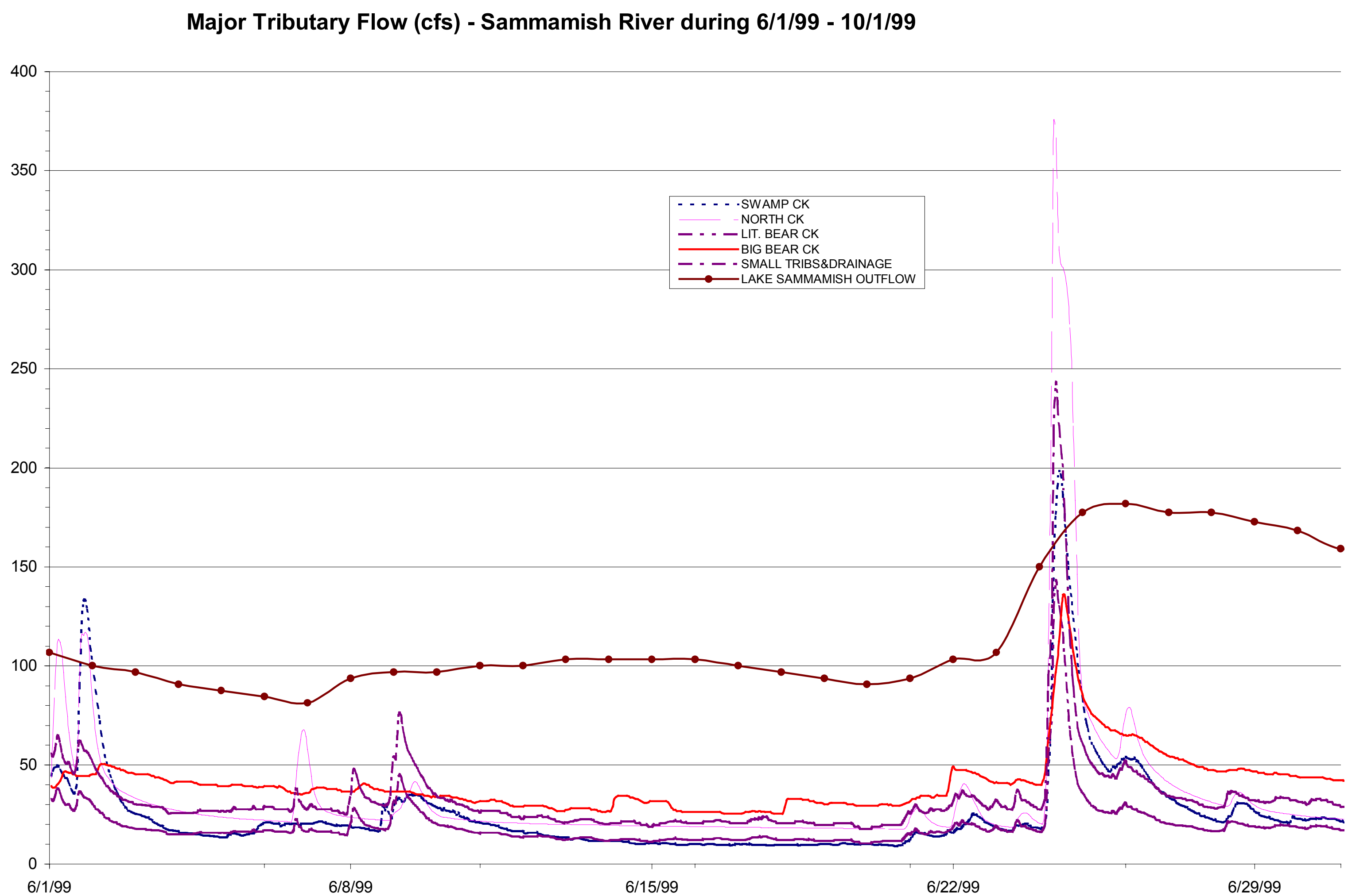


Figure 7-2 1999 Sammamish River inflow and tributary inflow temperature timeseries

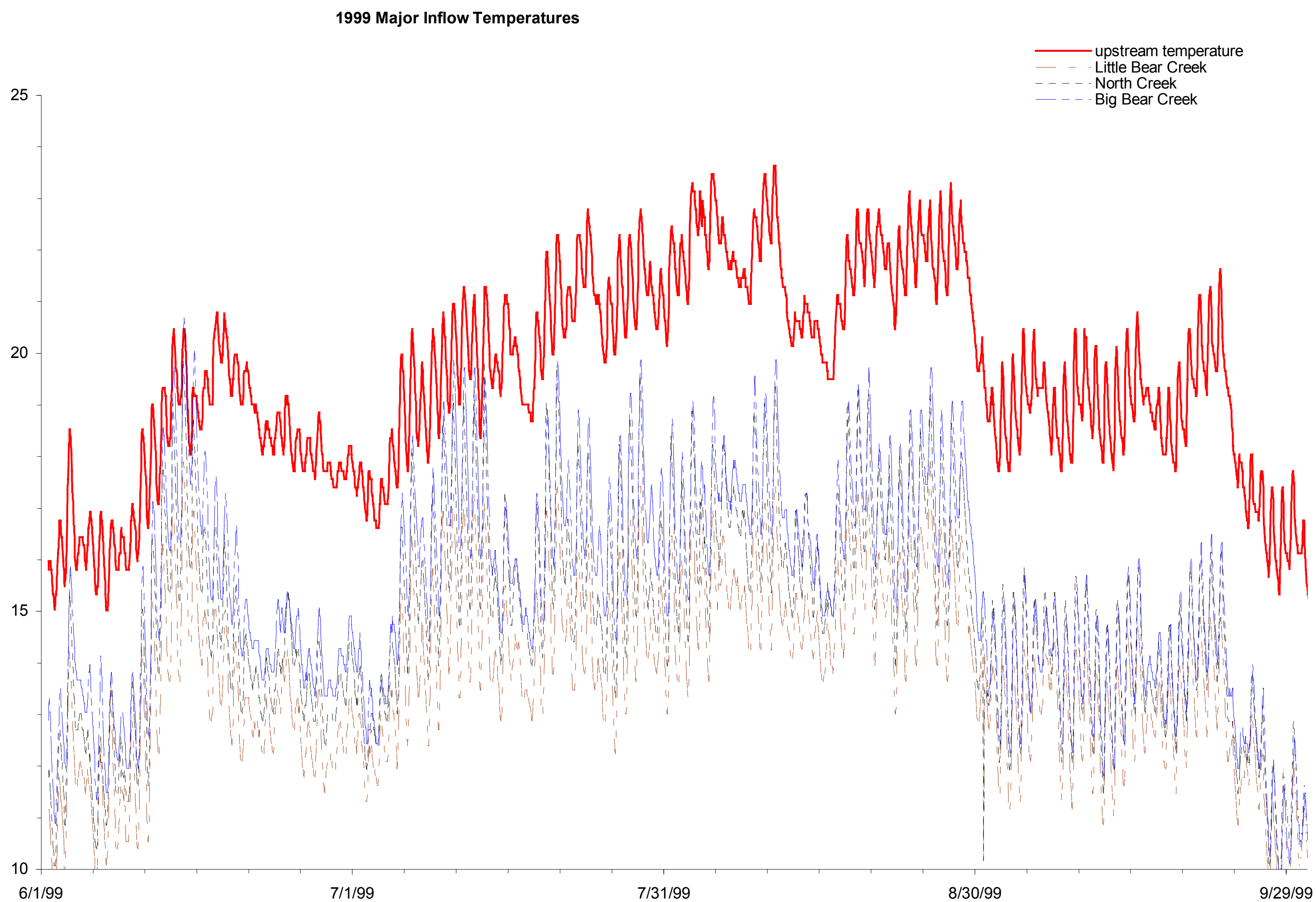


Figure 7-3 1999 computed and observed temperature time series at the Railroad Bridge

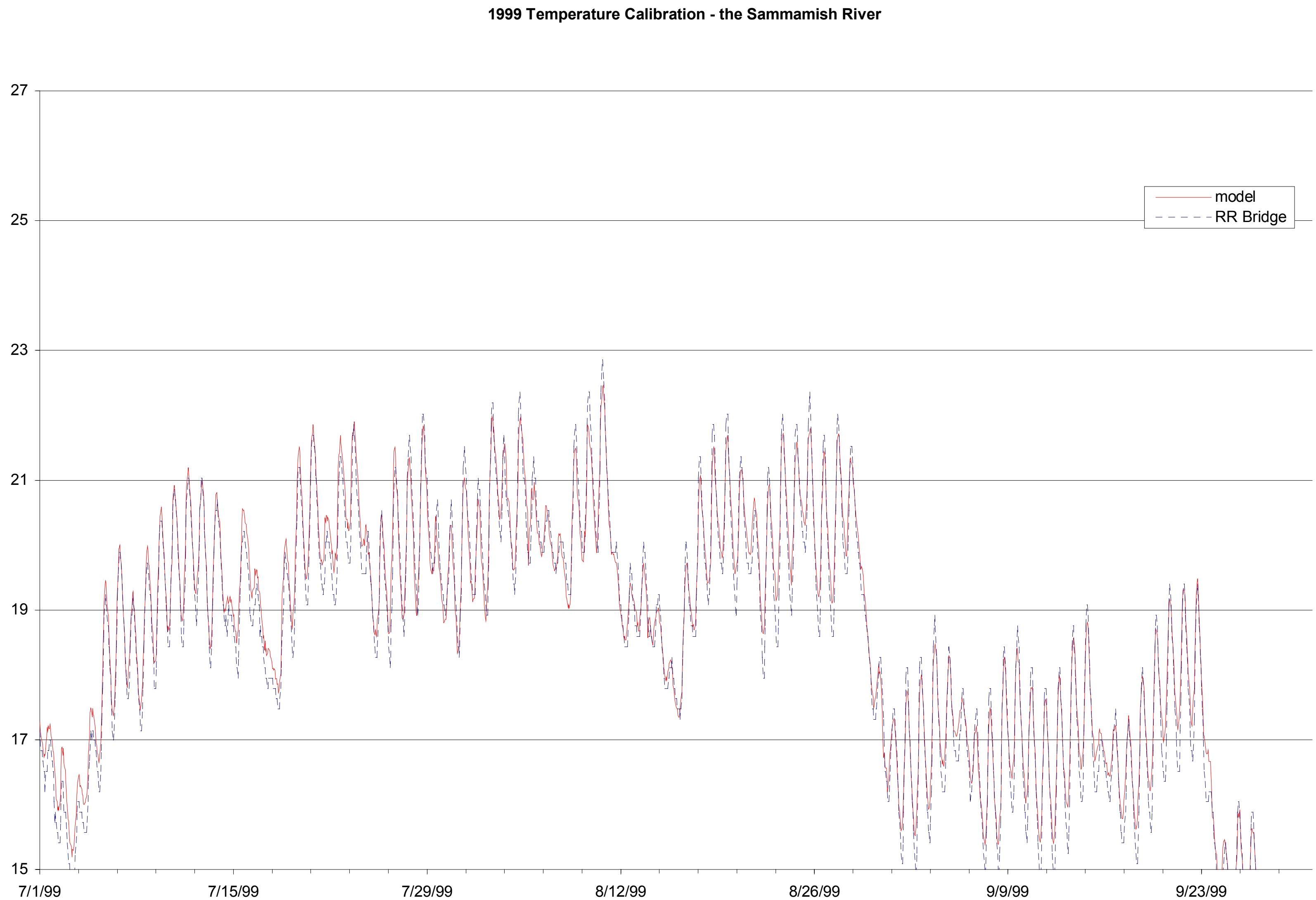


Figure 7-4 1999 computed and observed temperature time series at the 116th Street Bridge

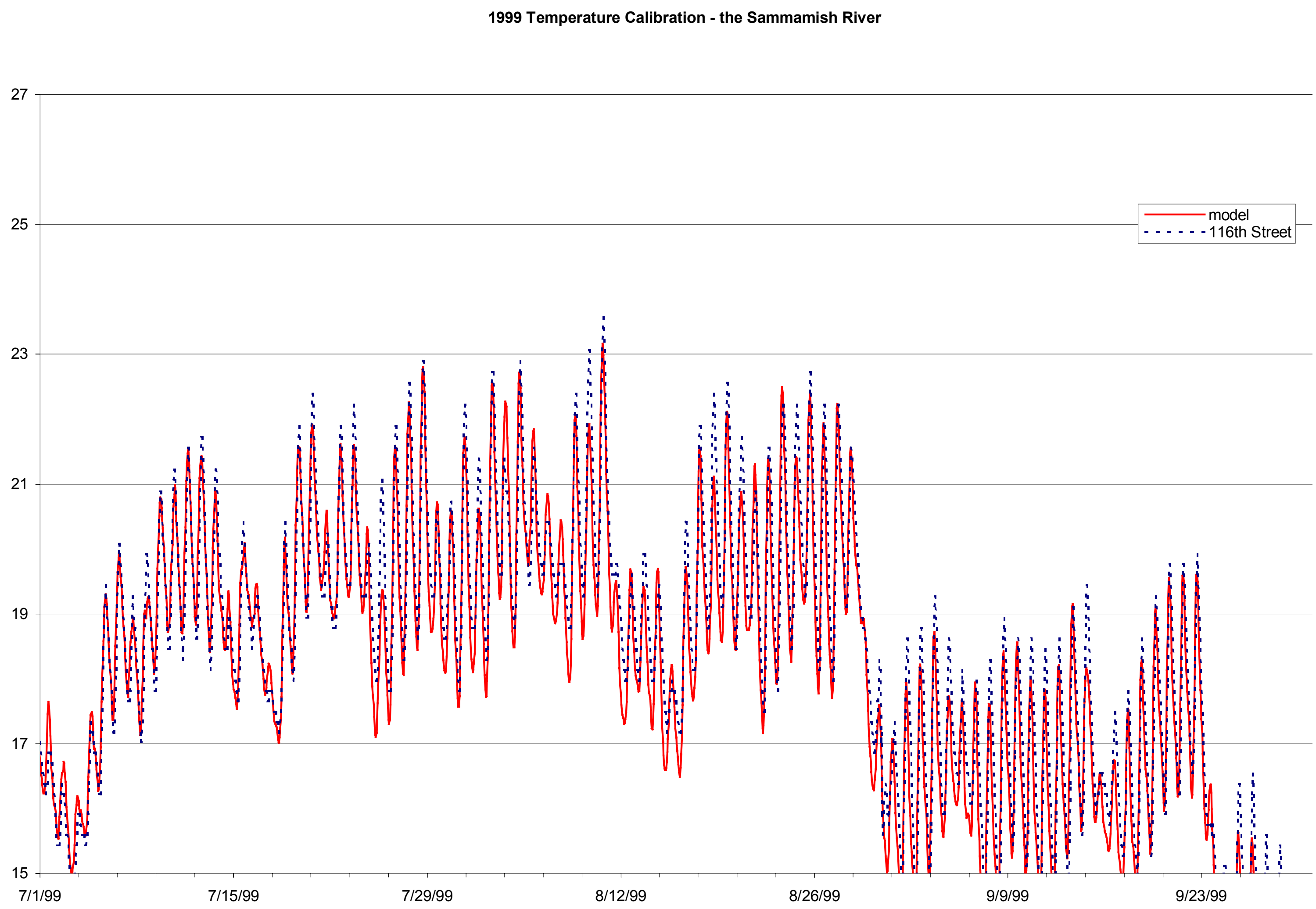


Figure 7-5 1999 computed and observed temperature time series at the 124th Street Bridge

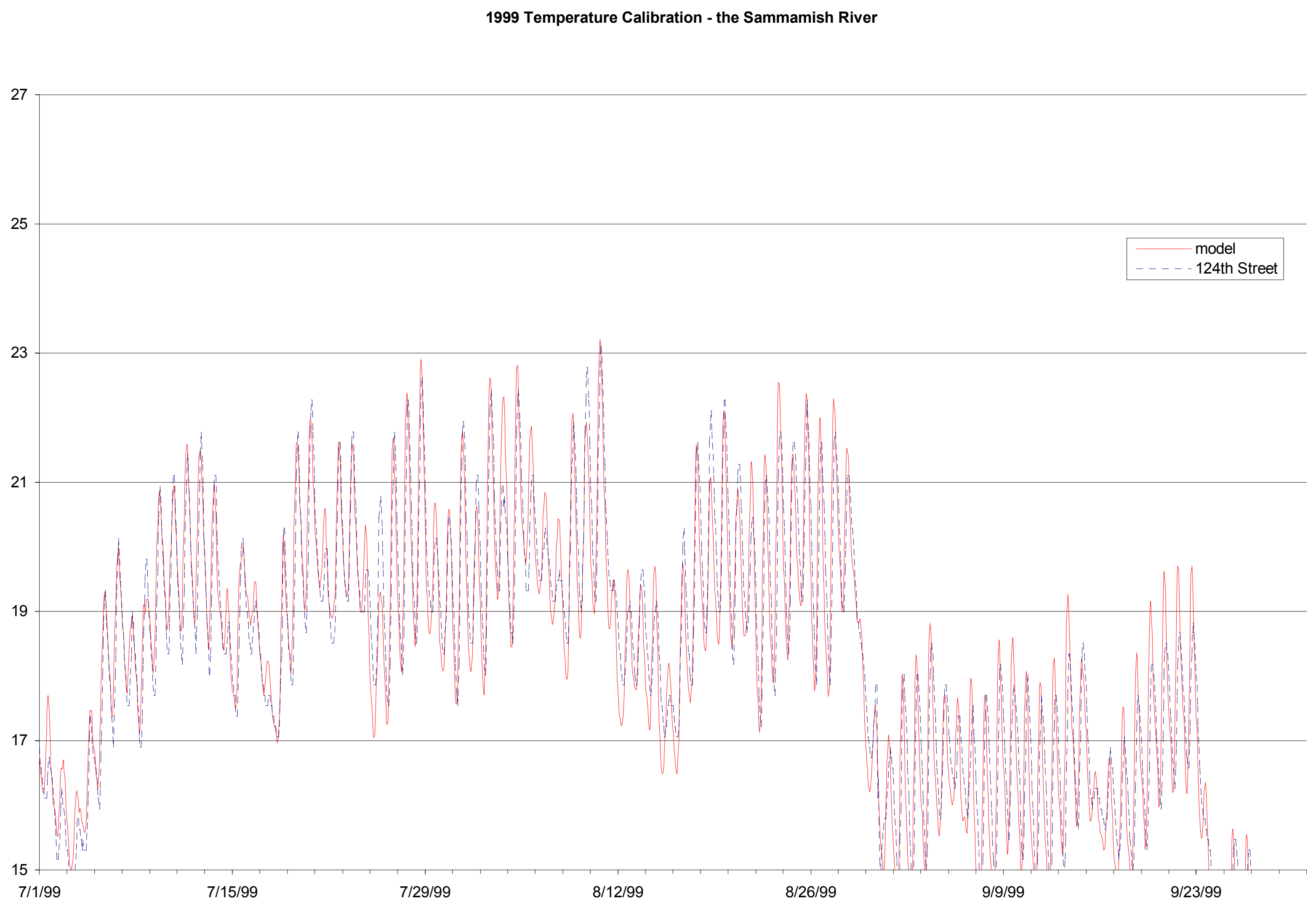


Figure 7-6 1999 computed and observed temperature time series at the 145th Street Bridge

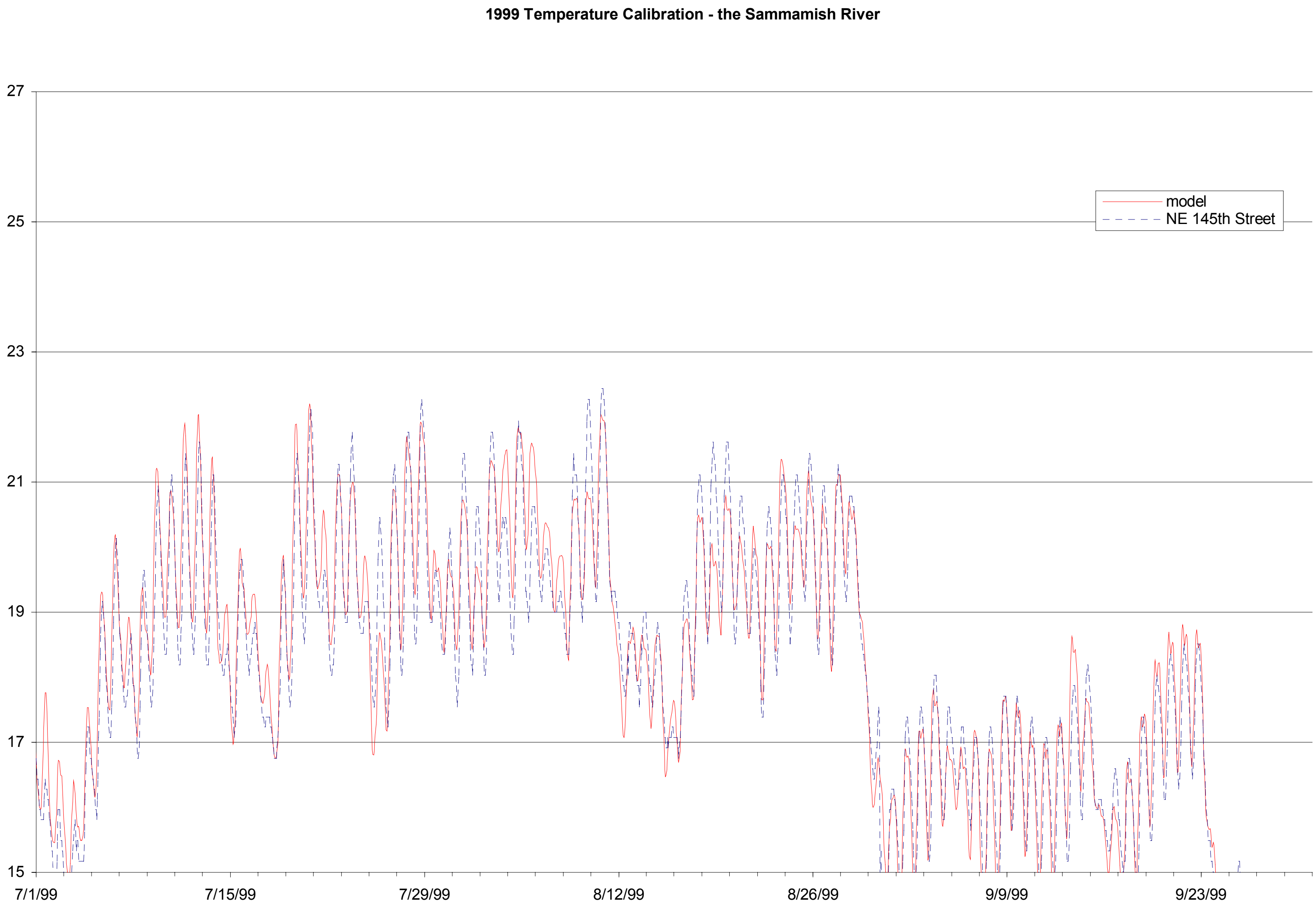


Figure 7-7 1999 computed and observed temperature time series at the Blythe Park

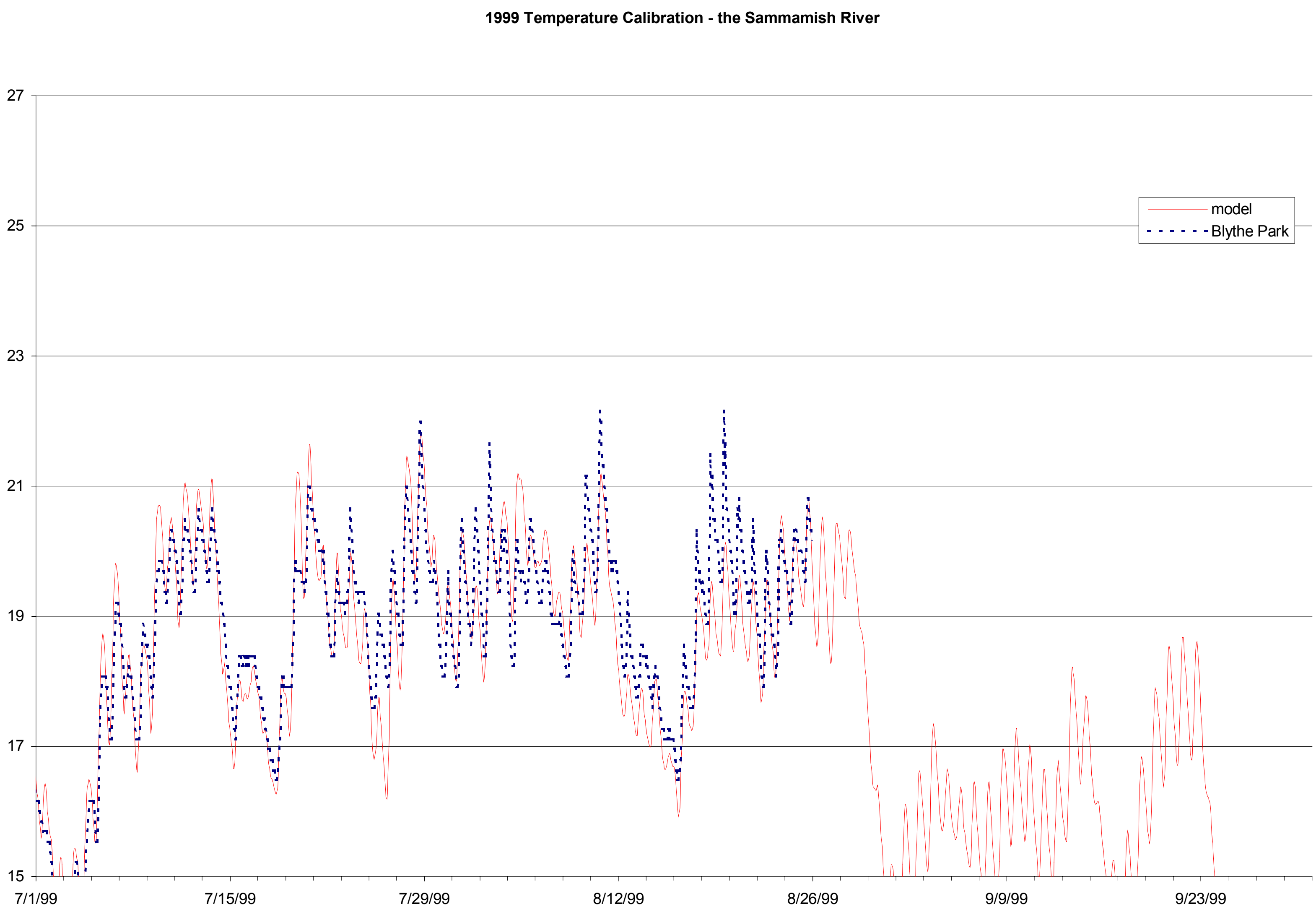


Figure 7-8 1998 Sammamish River inflow and tributary inflow time series

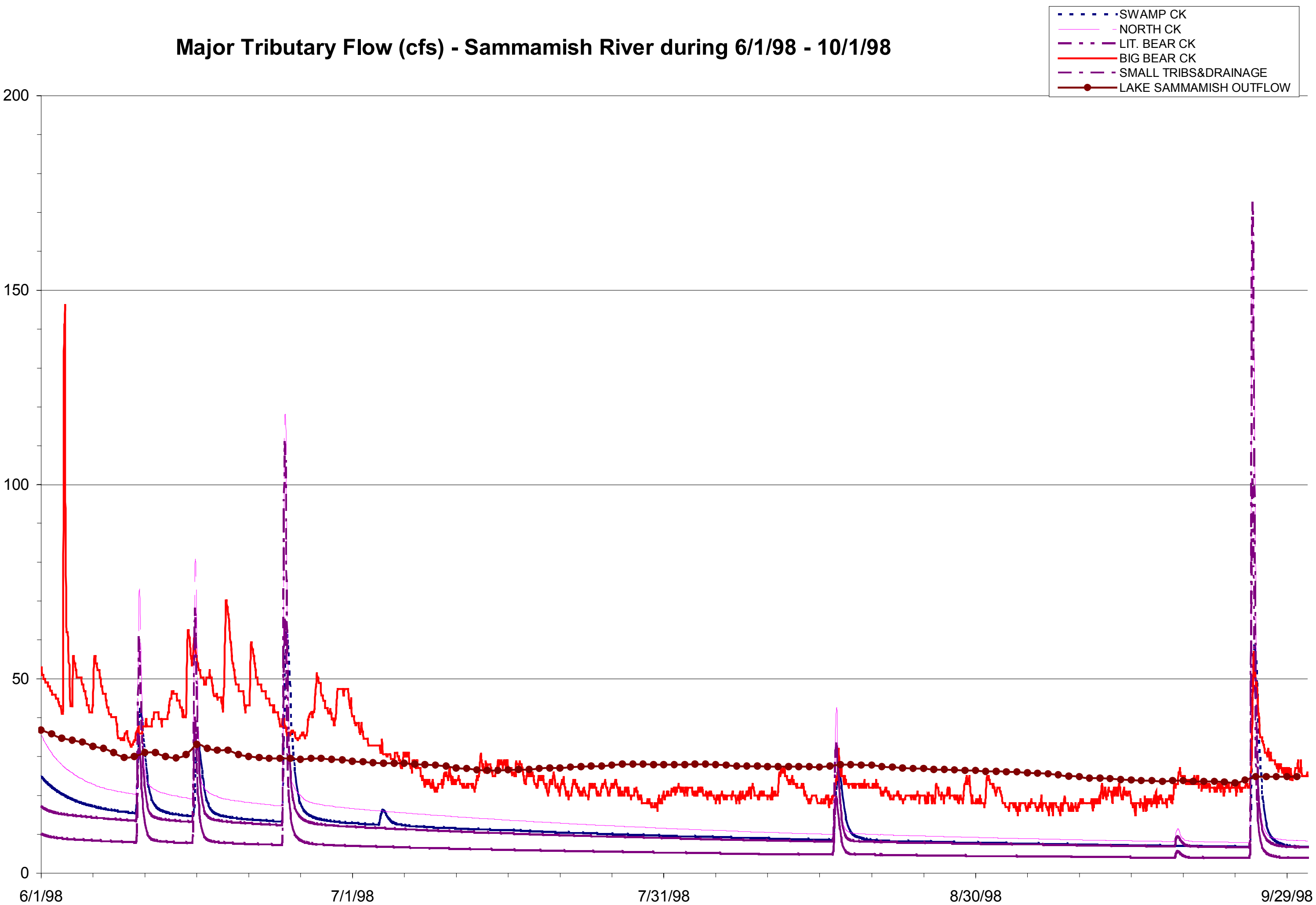


Figure 7-9 1998 Sammamish River inflow and tributary inflow temperature time series

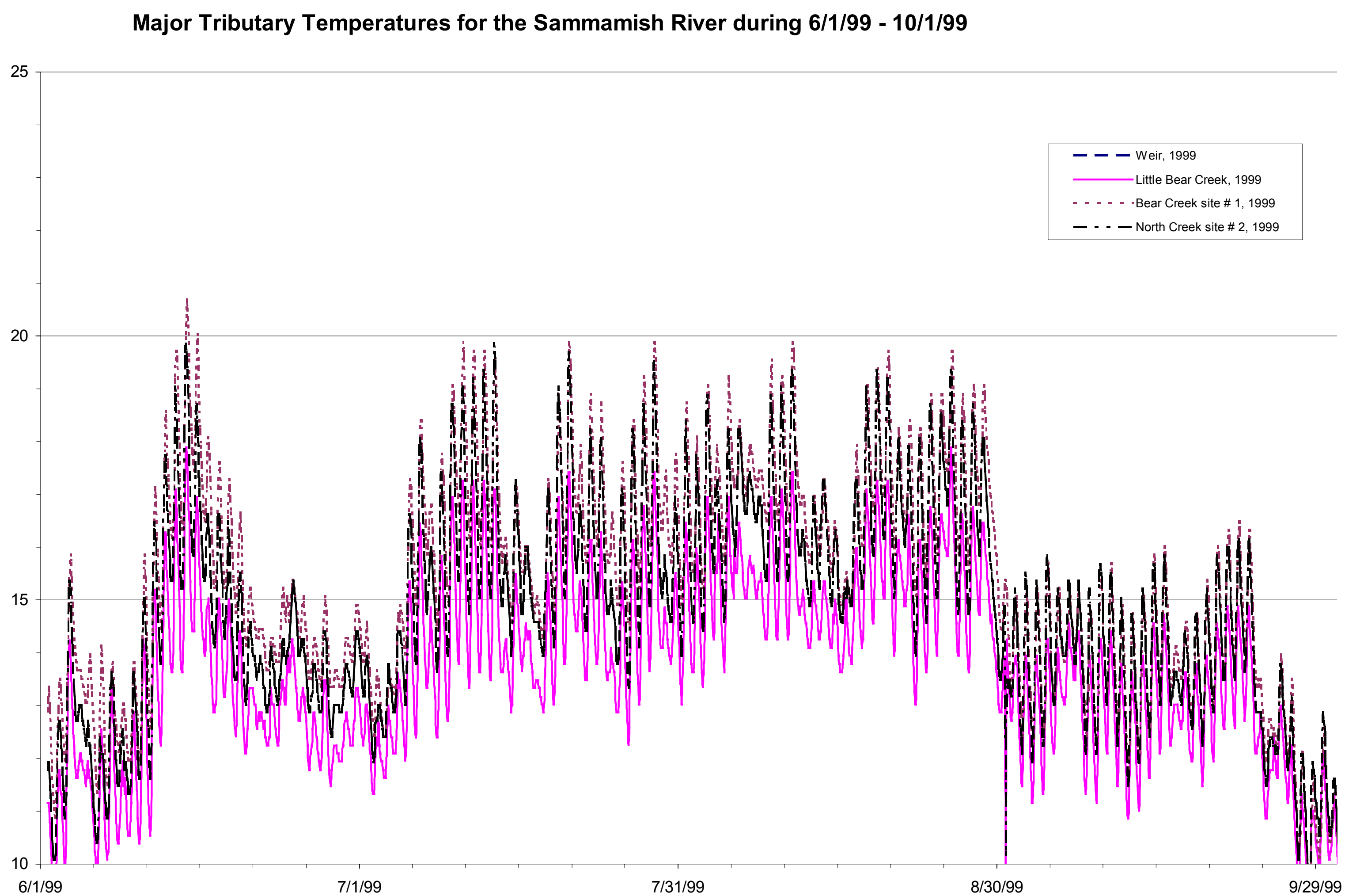


Figure 7-10 1998 computed and observed temperature time series at the Railroad Bridge

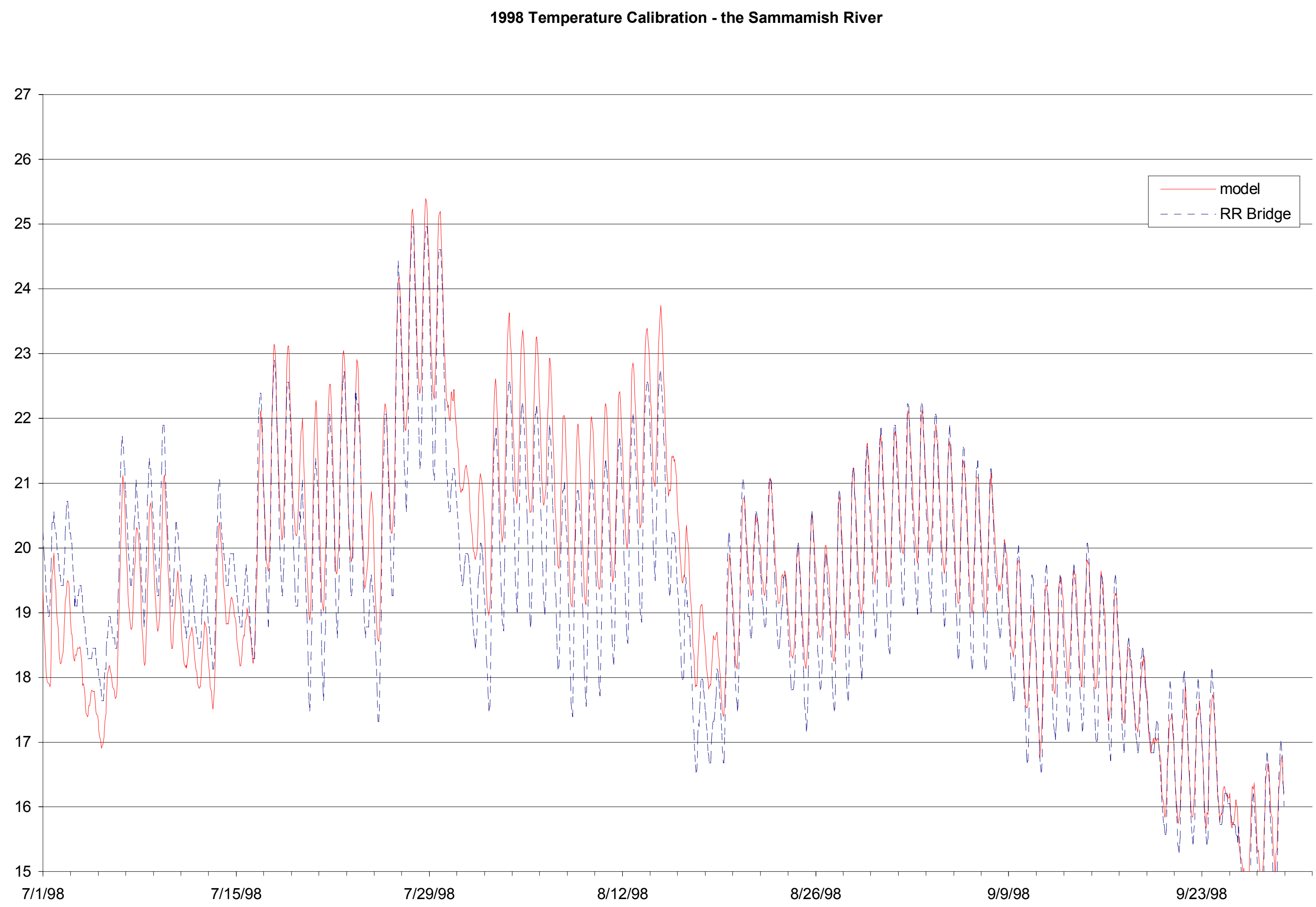


Figure 7-11 1998 computed and observed temperature time series at the 116th Street Bridge

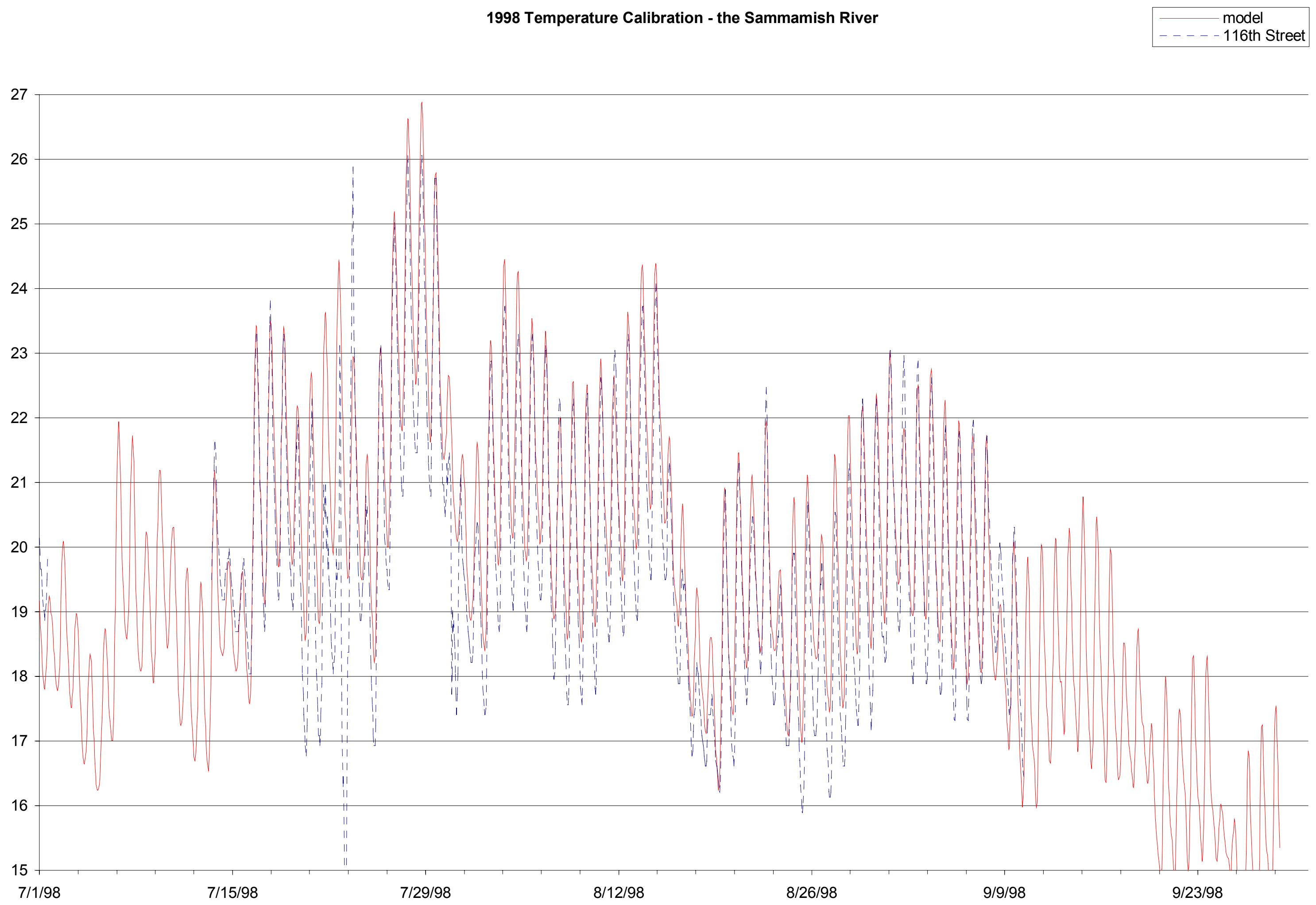


Figure 7-12 1998 computed and observed temperature time series at the 132nd Street Bridge

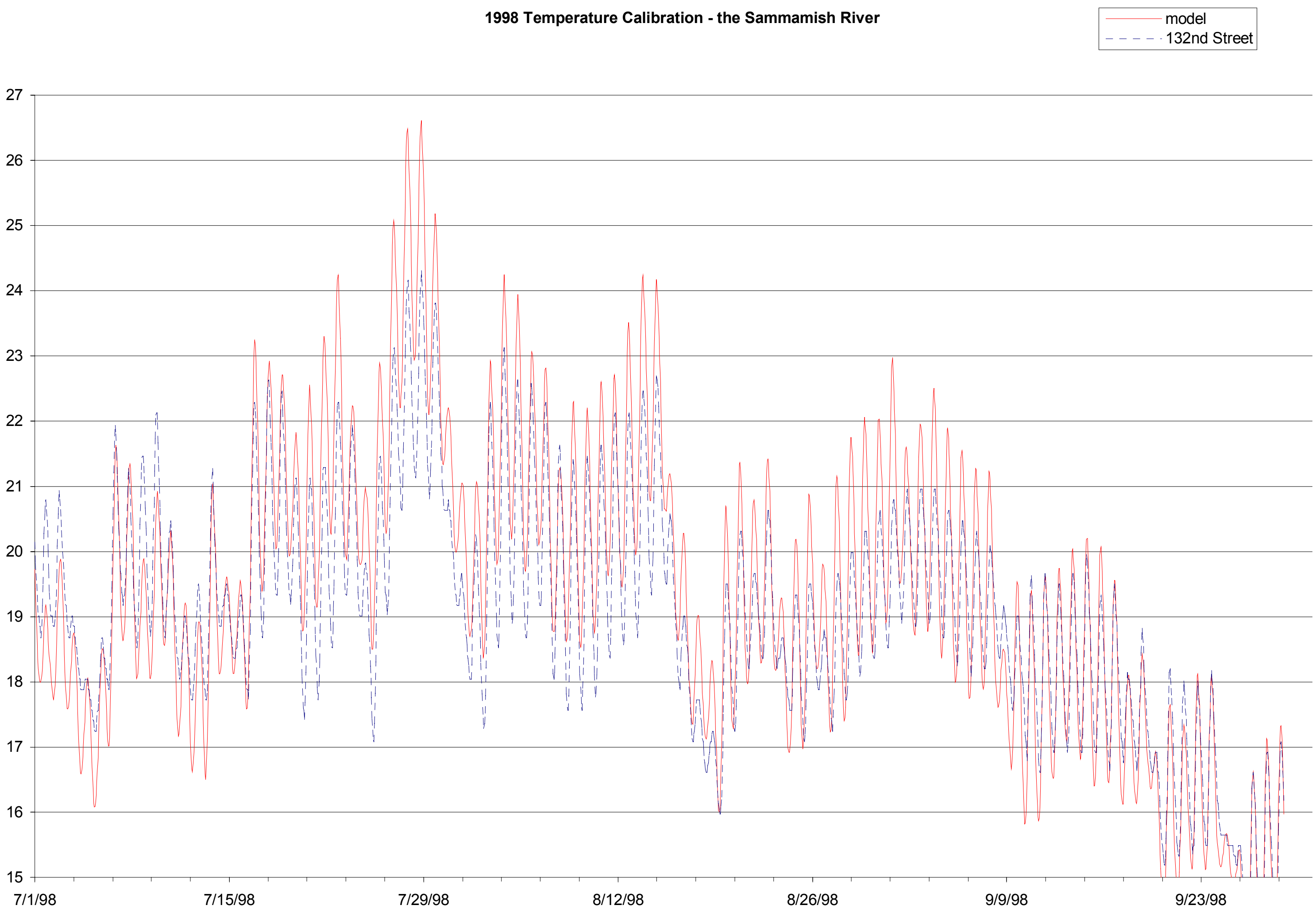


Figure 7-13 1998 computed and observed temperature time series at the 145th Street Bridge

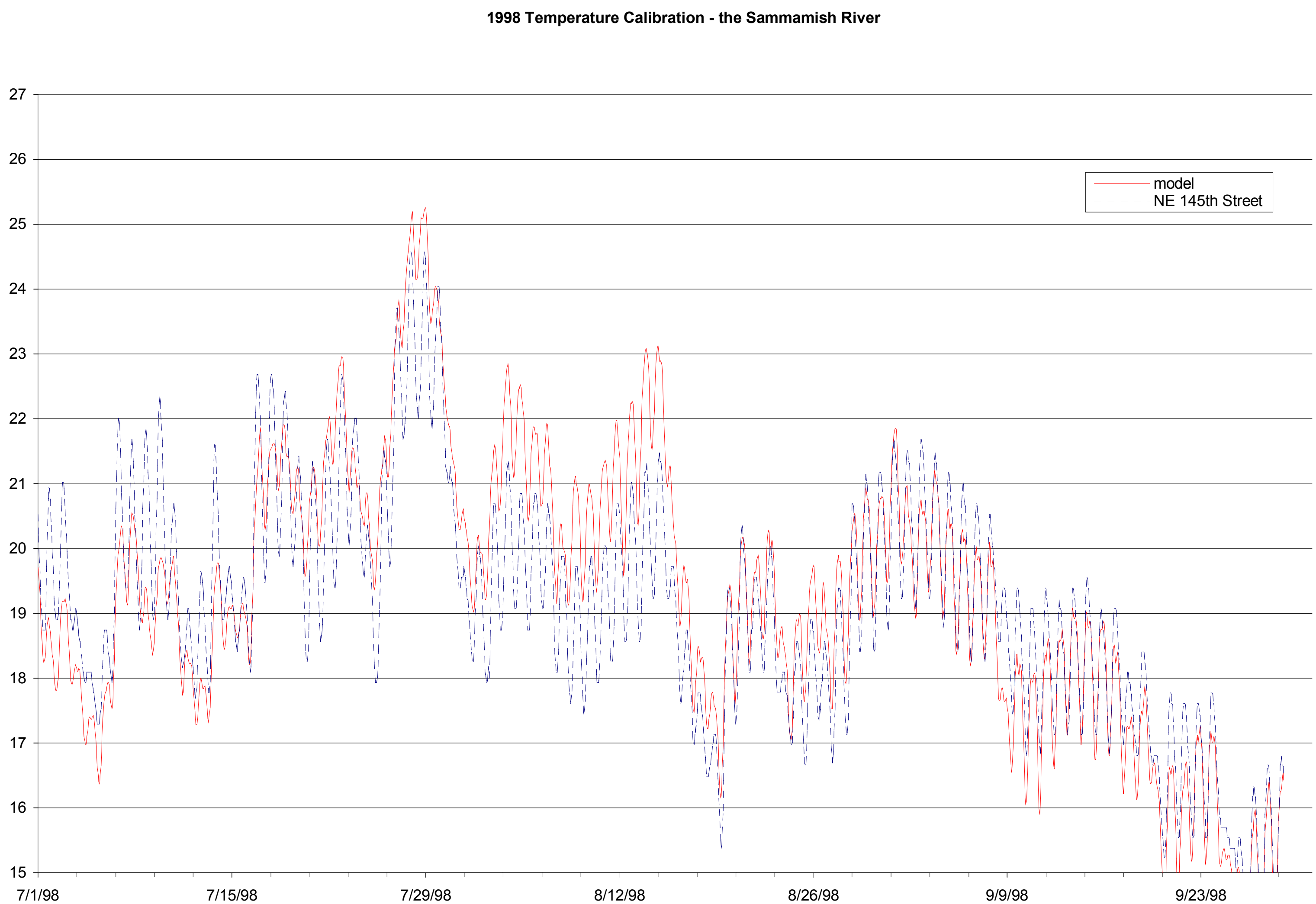


Figure 7-14 1998 computed and observed temperature time series at the Blythe Park

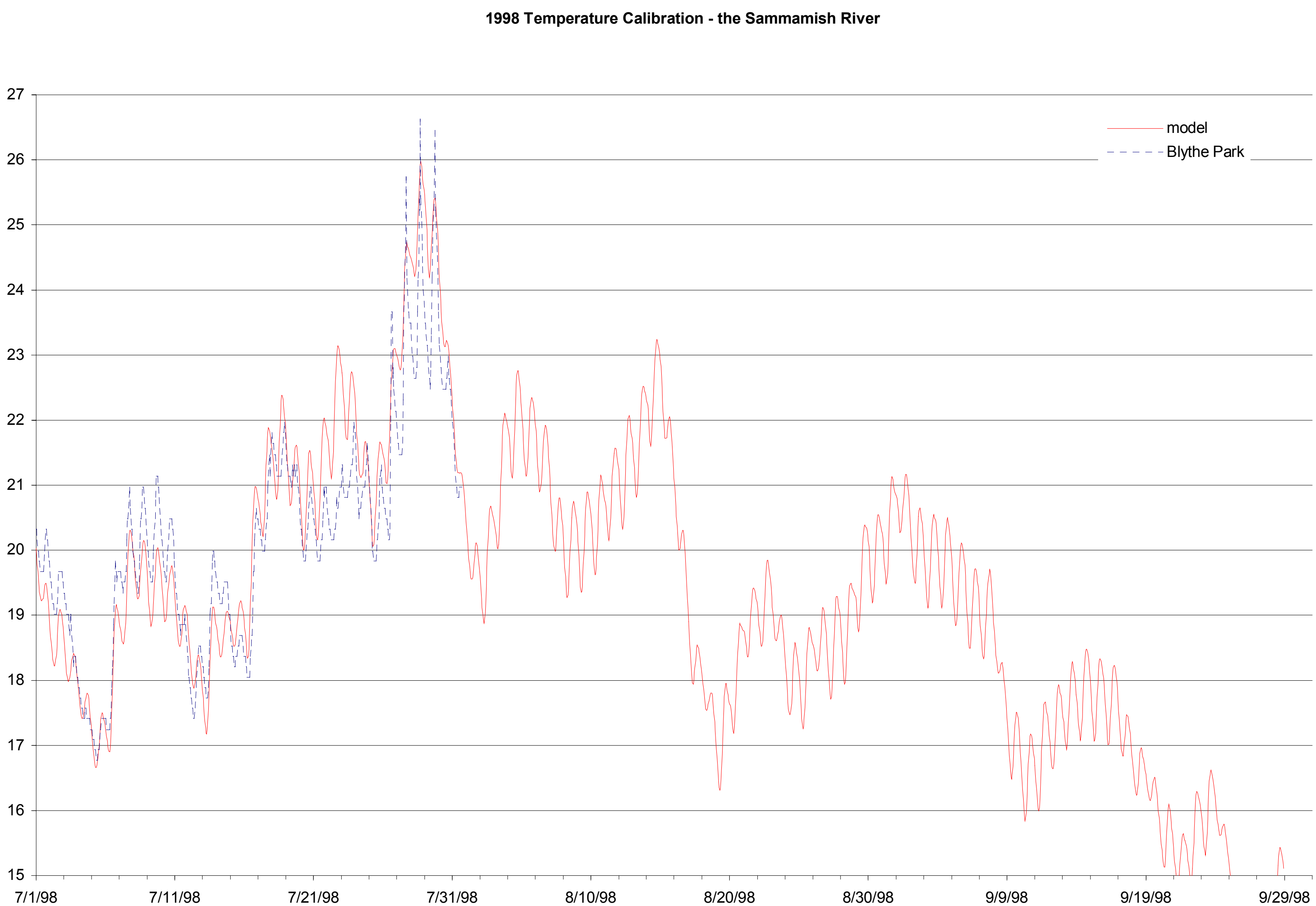


Figure 7-15 1999 observed RR Bridge temperatures compared to temperature of mixed Weir and Bear Creek flows

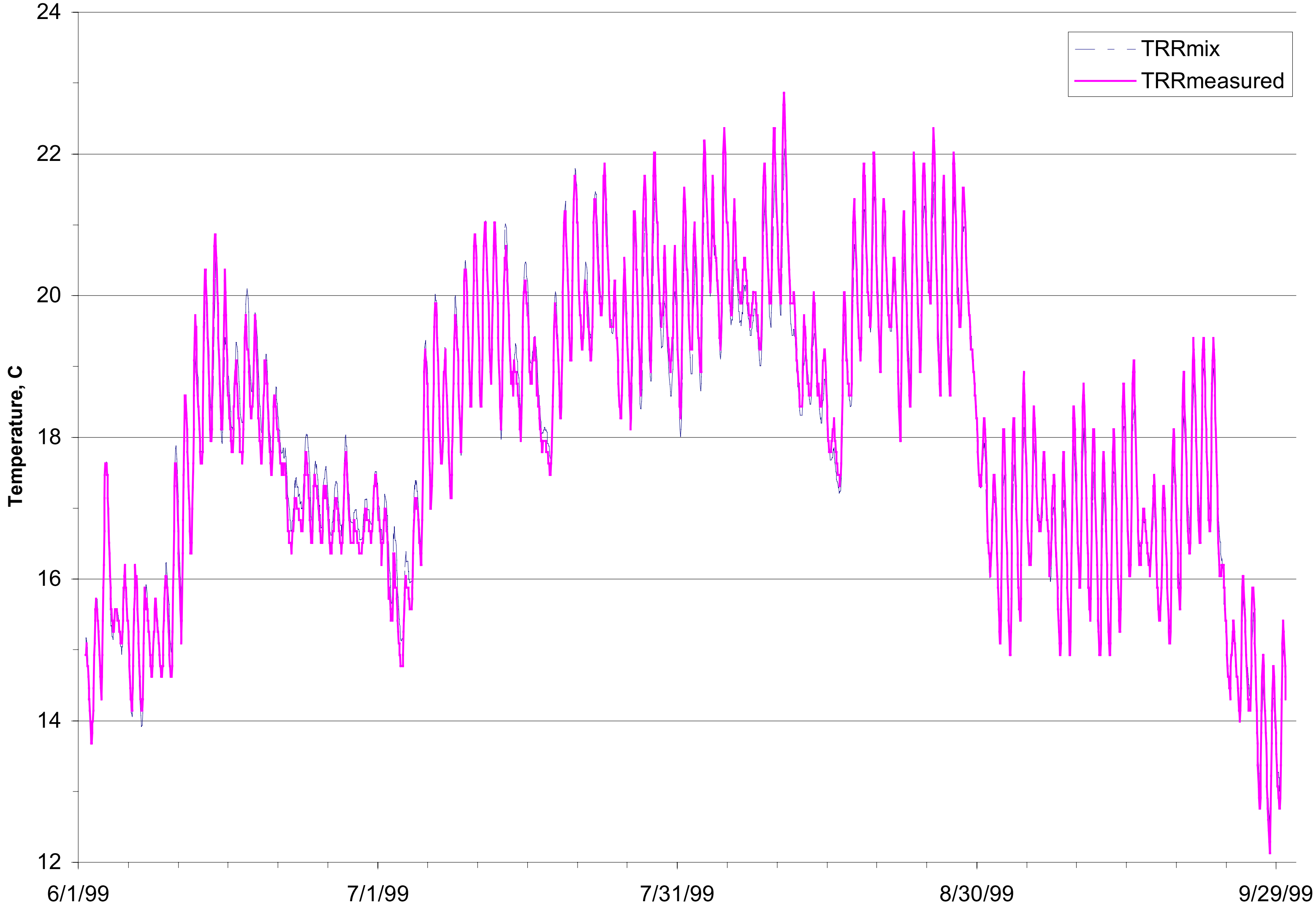


Figure 7-16 1998 observed RR Bridge temperatures compared to temperature of mixed Weir and Bear Creek flows

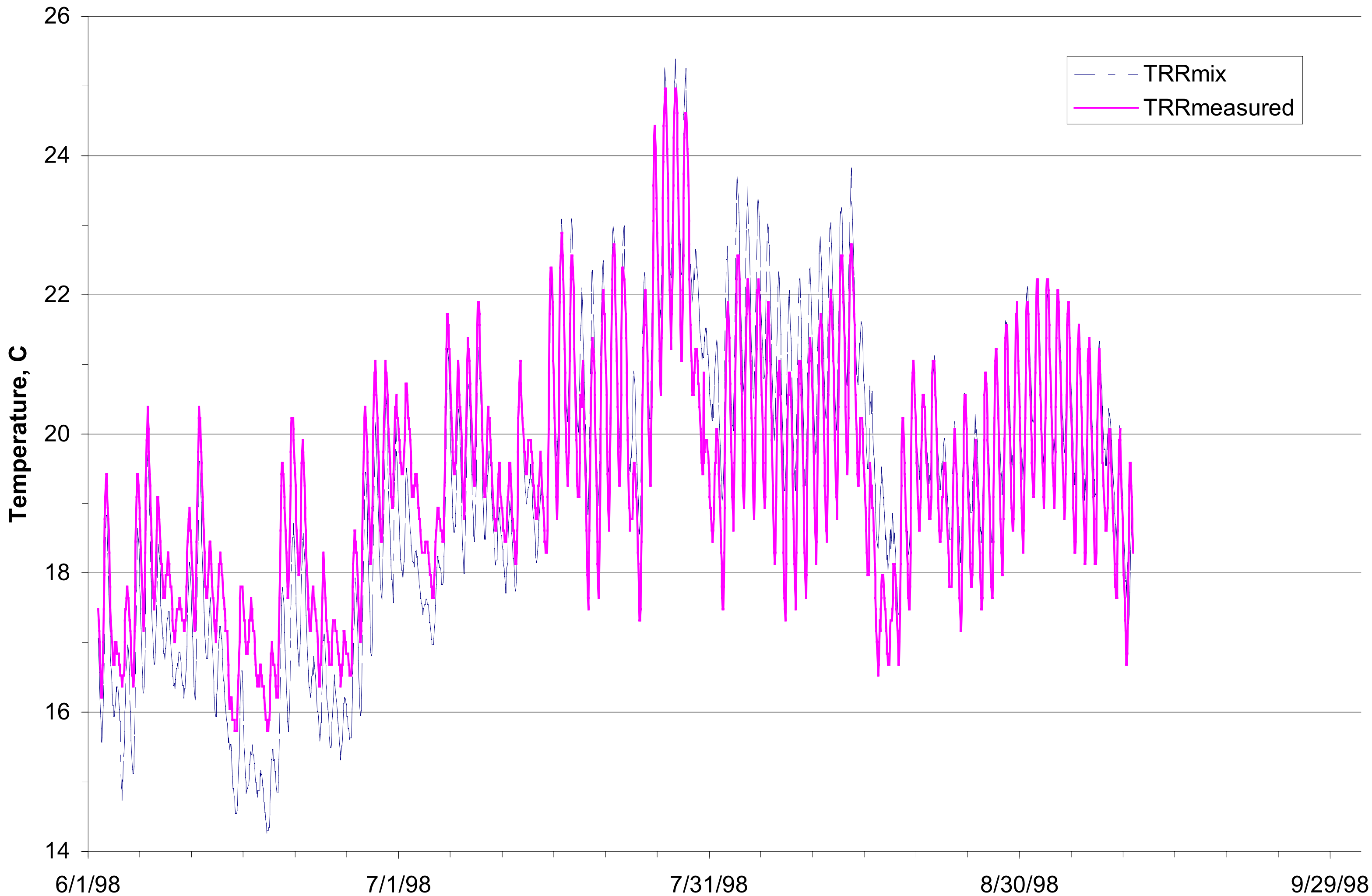


Figure 7-17 Base-case simulation – hourly output

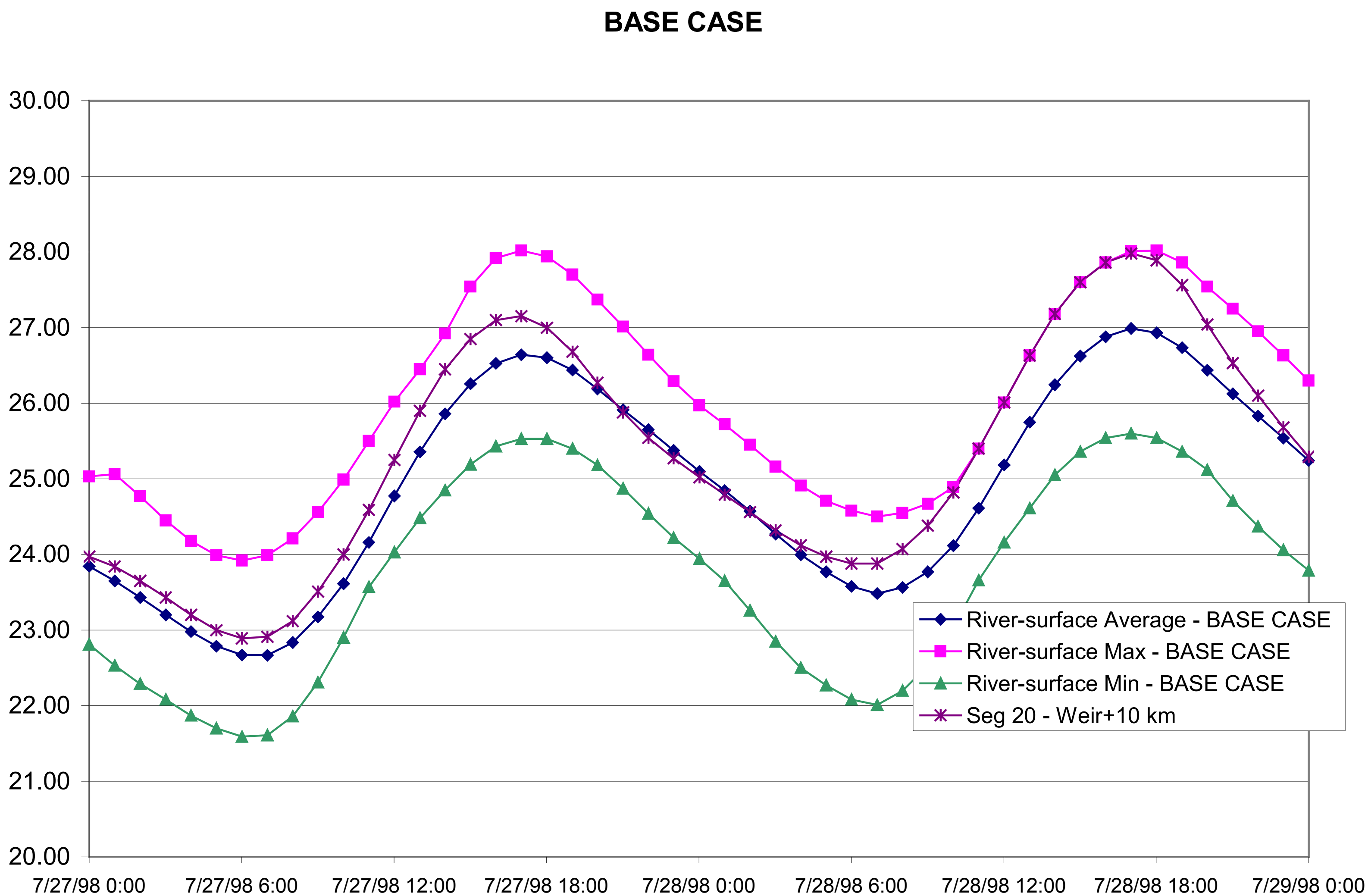


Figure 7-18 Base-case simulation – surface temperature longitudinal profile

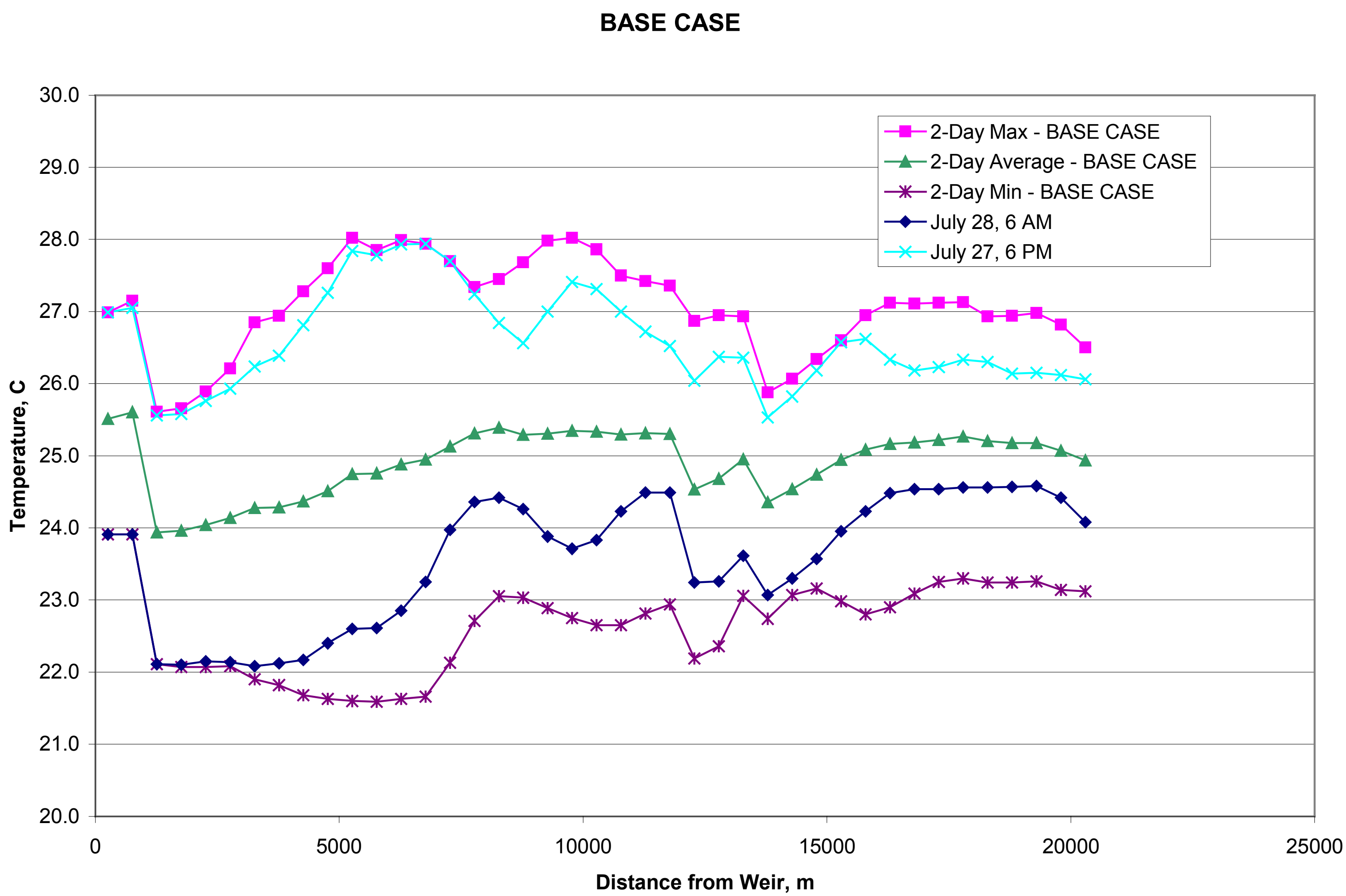


Figure 7-19 Groundwater Augmentation Scenario 1 - hourly output

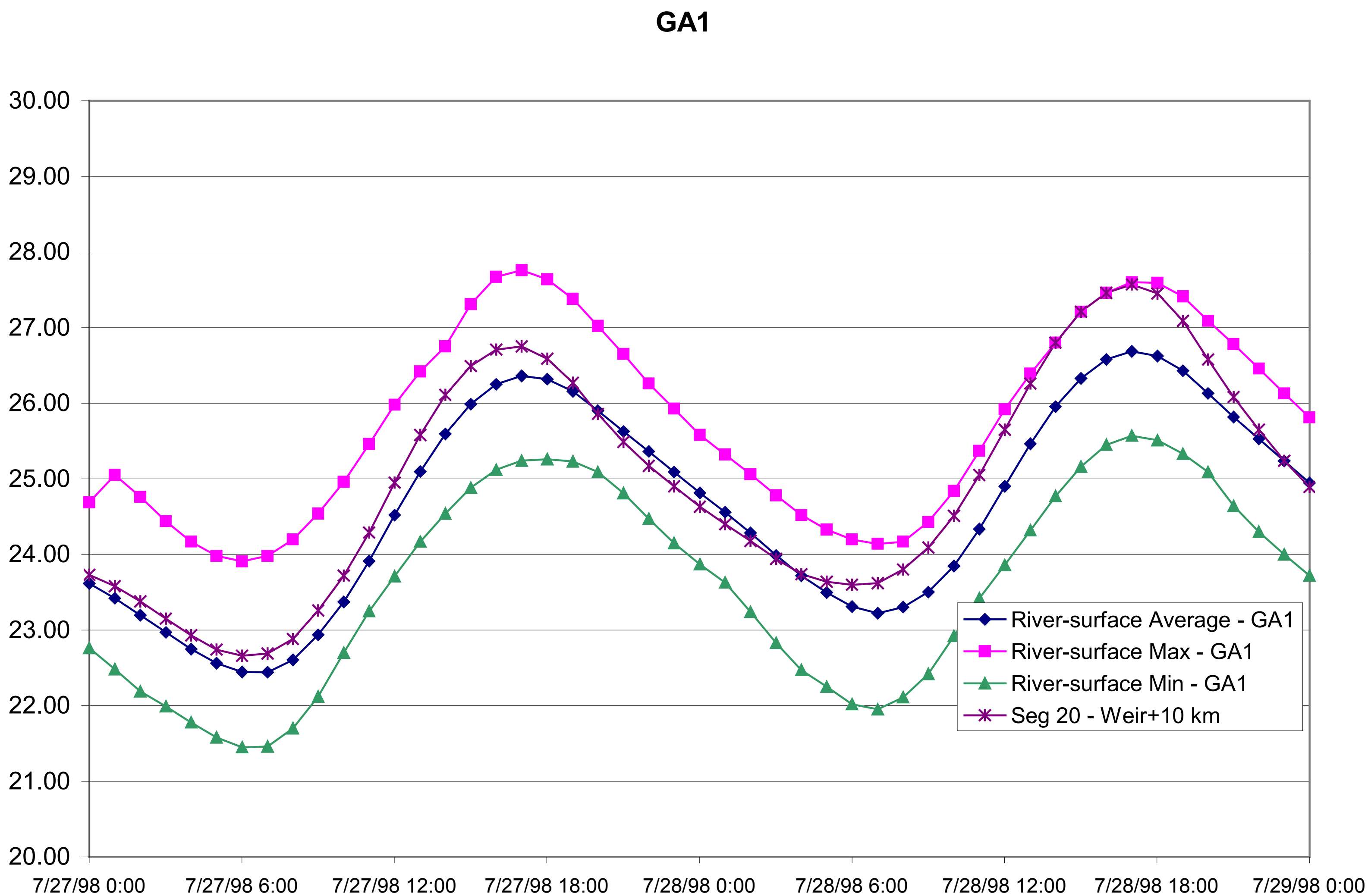


Figure 7-20 Groundwater Augmentation Scenario 1 – surface temperature longitudinal profile

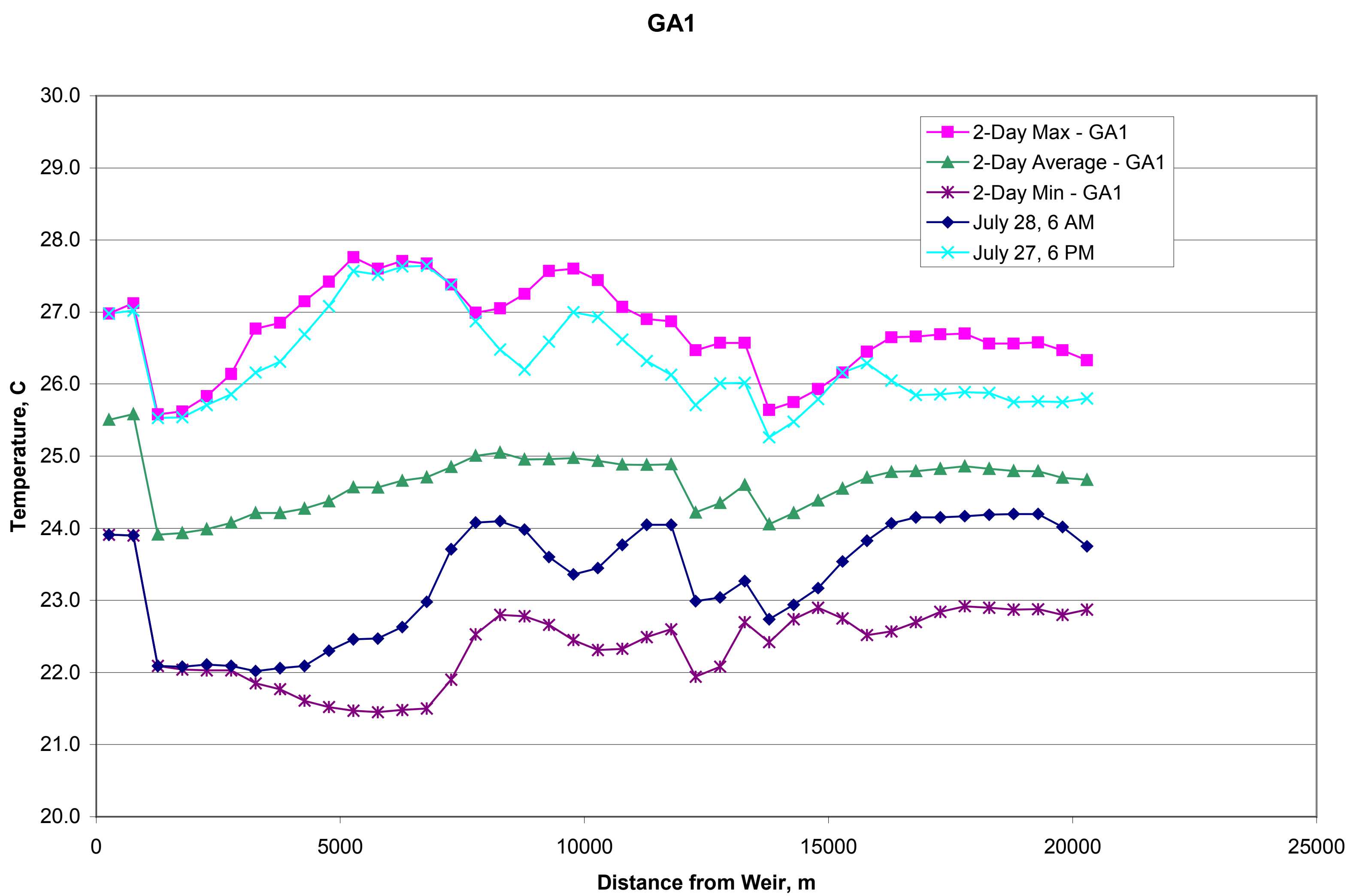


Figure 7-21 Groundwater Augmentation Scenario 3 - hourly output

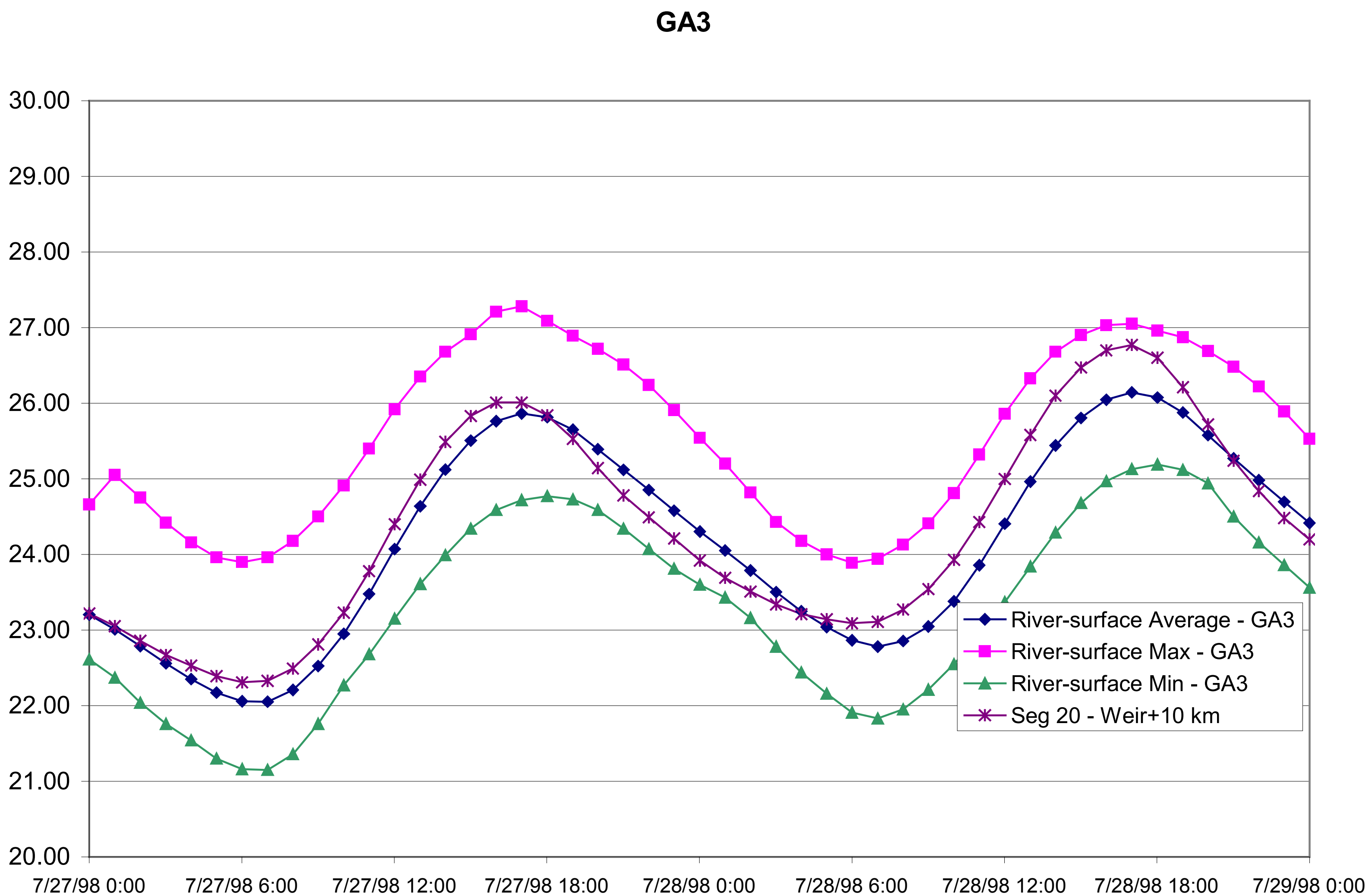


Figure 7-22 Groundwater Augmentation Scenario 3 – surface temperature longitudinal profile

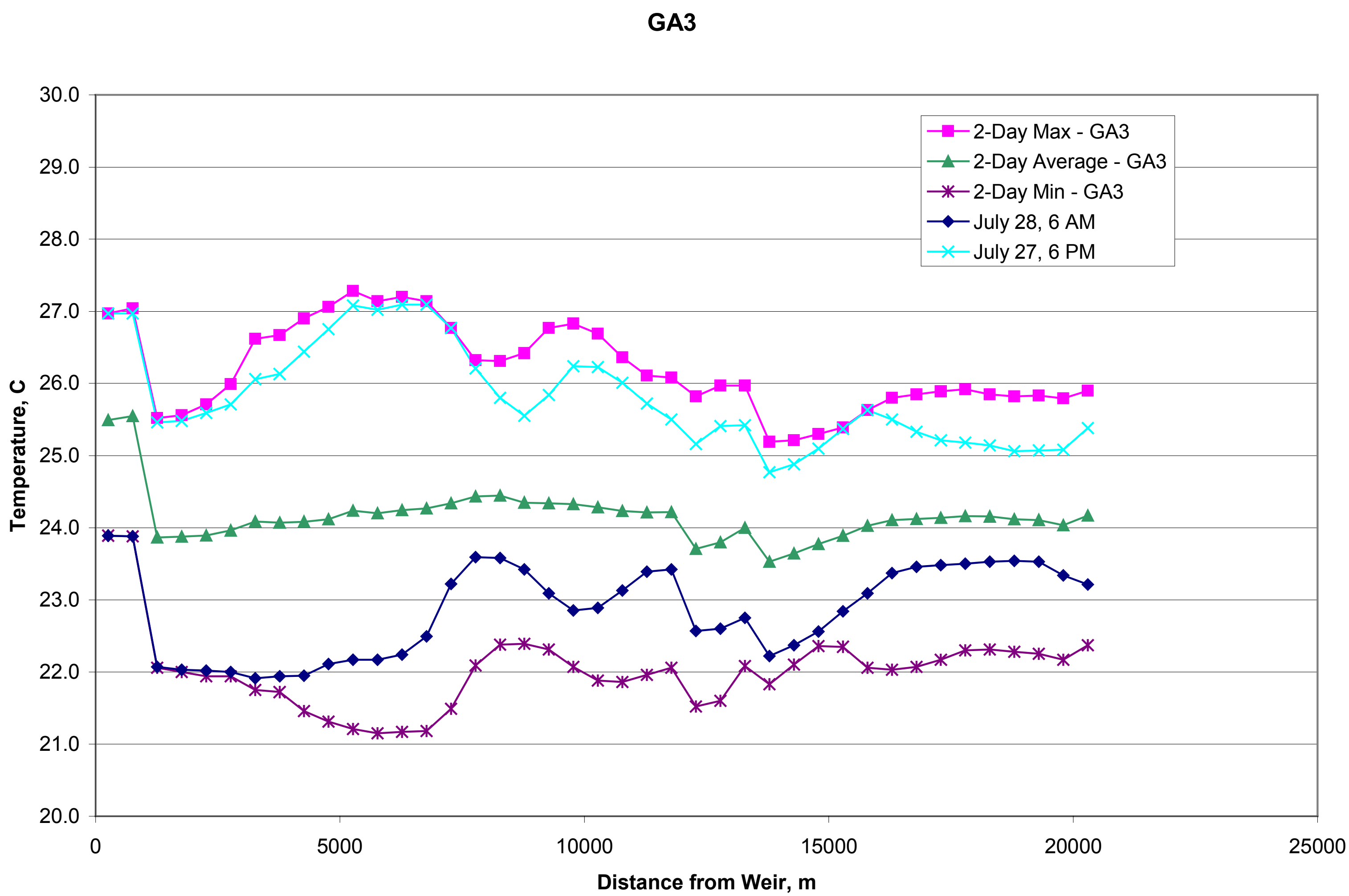


Figure 7-23 Surface-Restoration Scenario 3 – hourly output

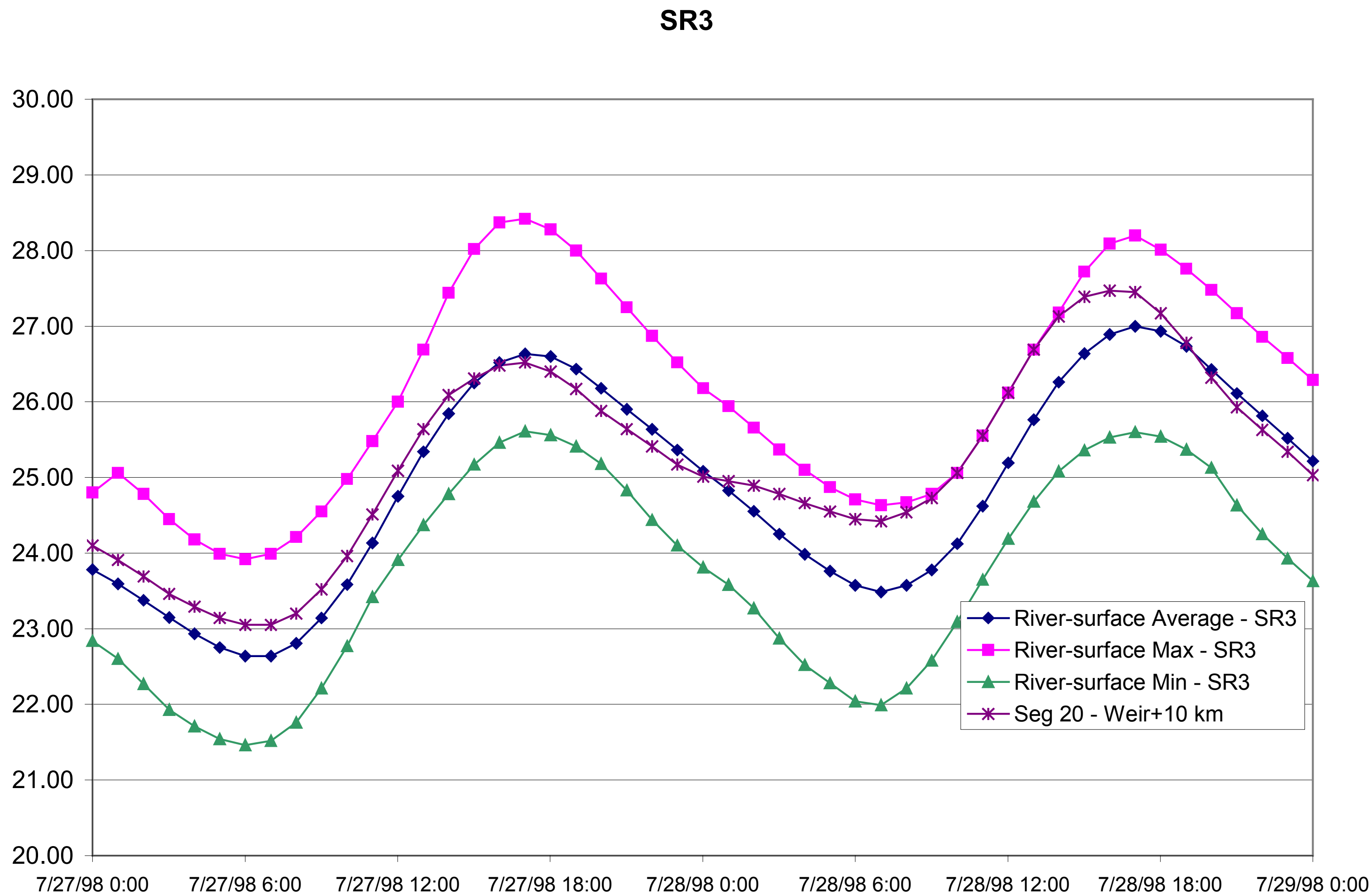


Figure 7-24 Surface-Restoration Scenario 3 – surface temperature longitudinal profile

Figure 7-25 Comparison of Scenarios – longitudinal profile of 2-day statistics

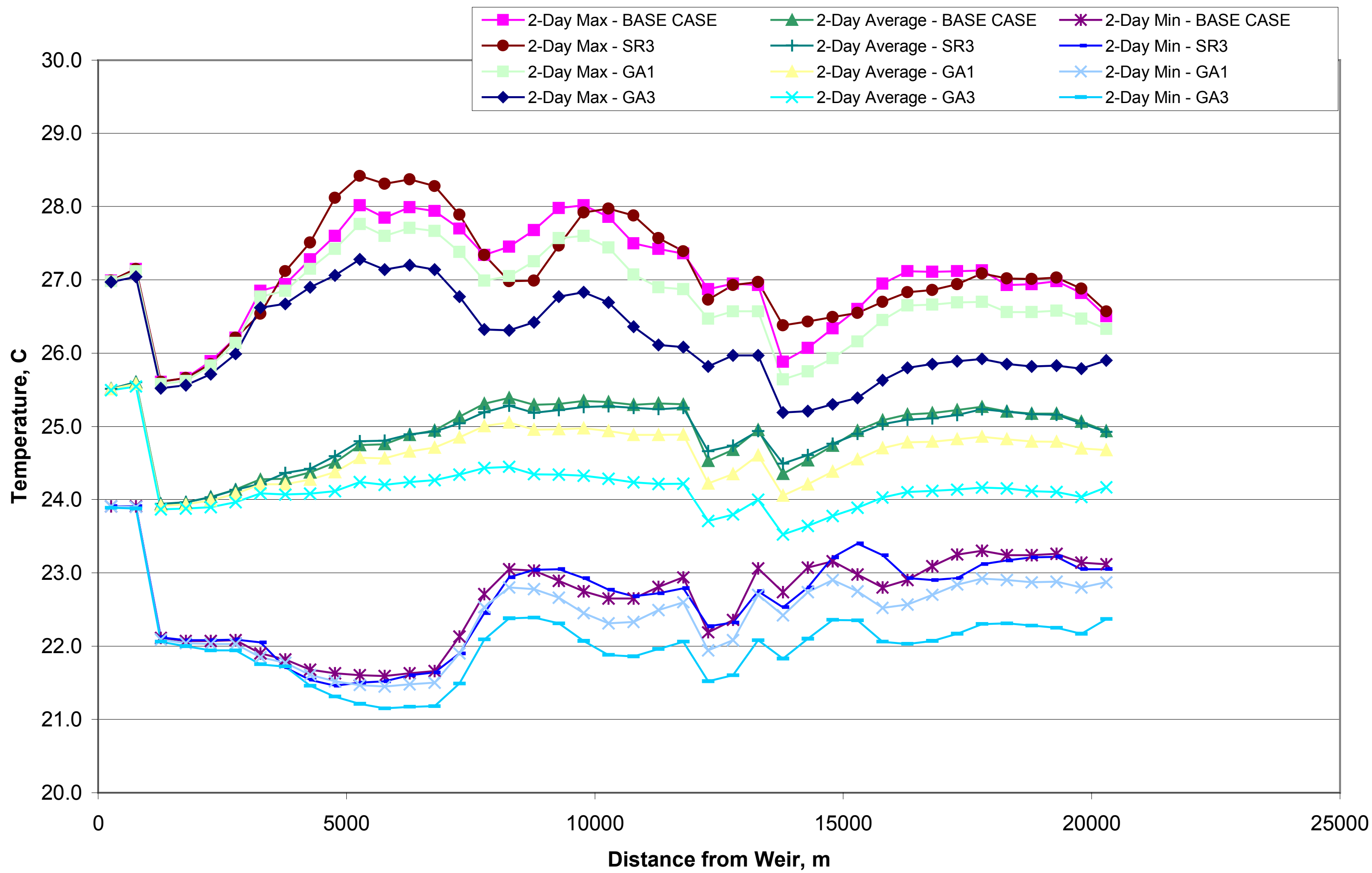


Figure 7-26 Comparison of Scenarios – longitudinal profiles of morning and evening temperatures

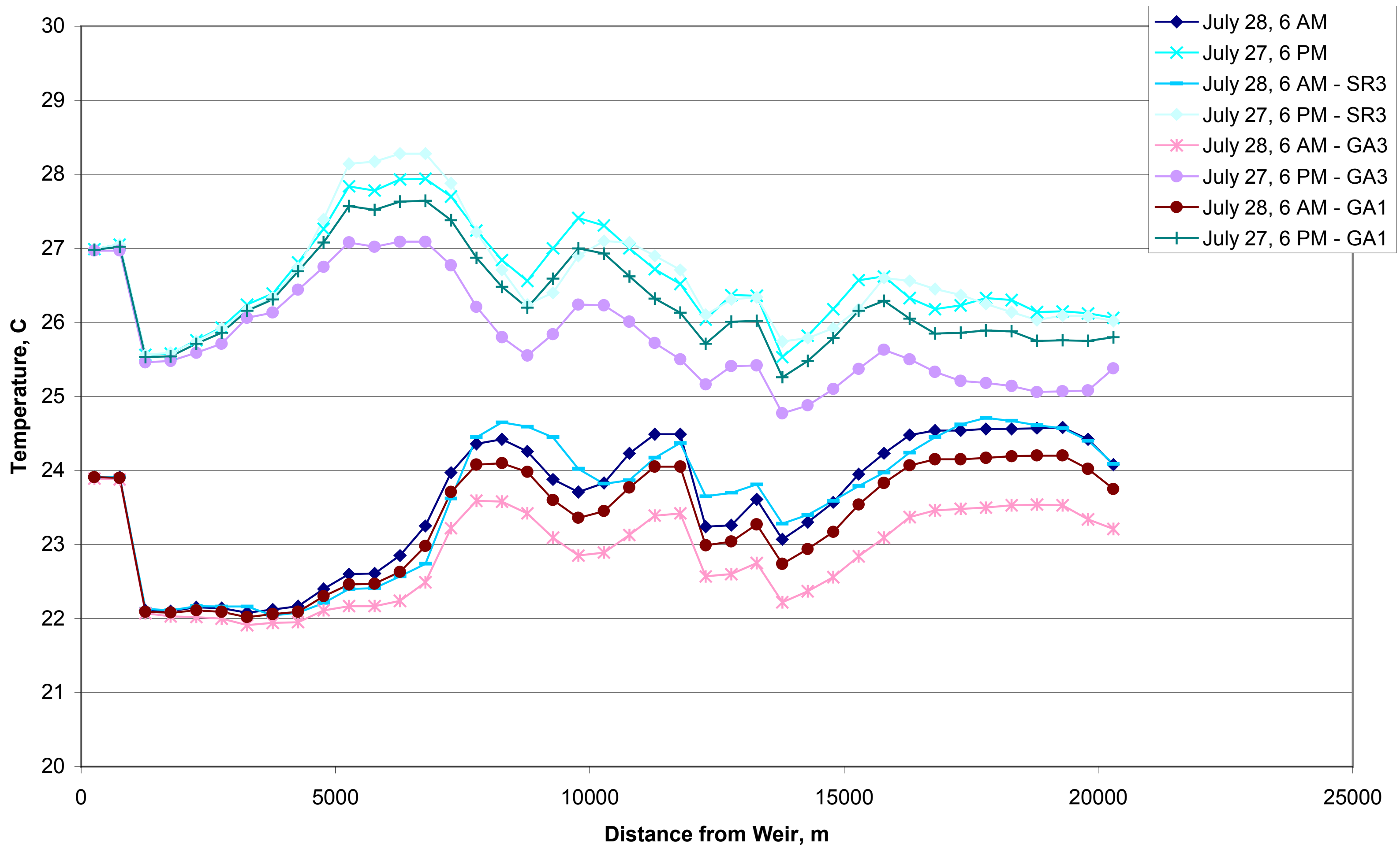


Figure 7-27 Comparison of Scenarios – hourly plot of maximum and average temperatures

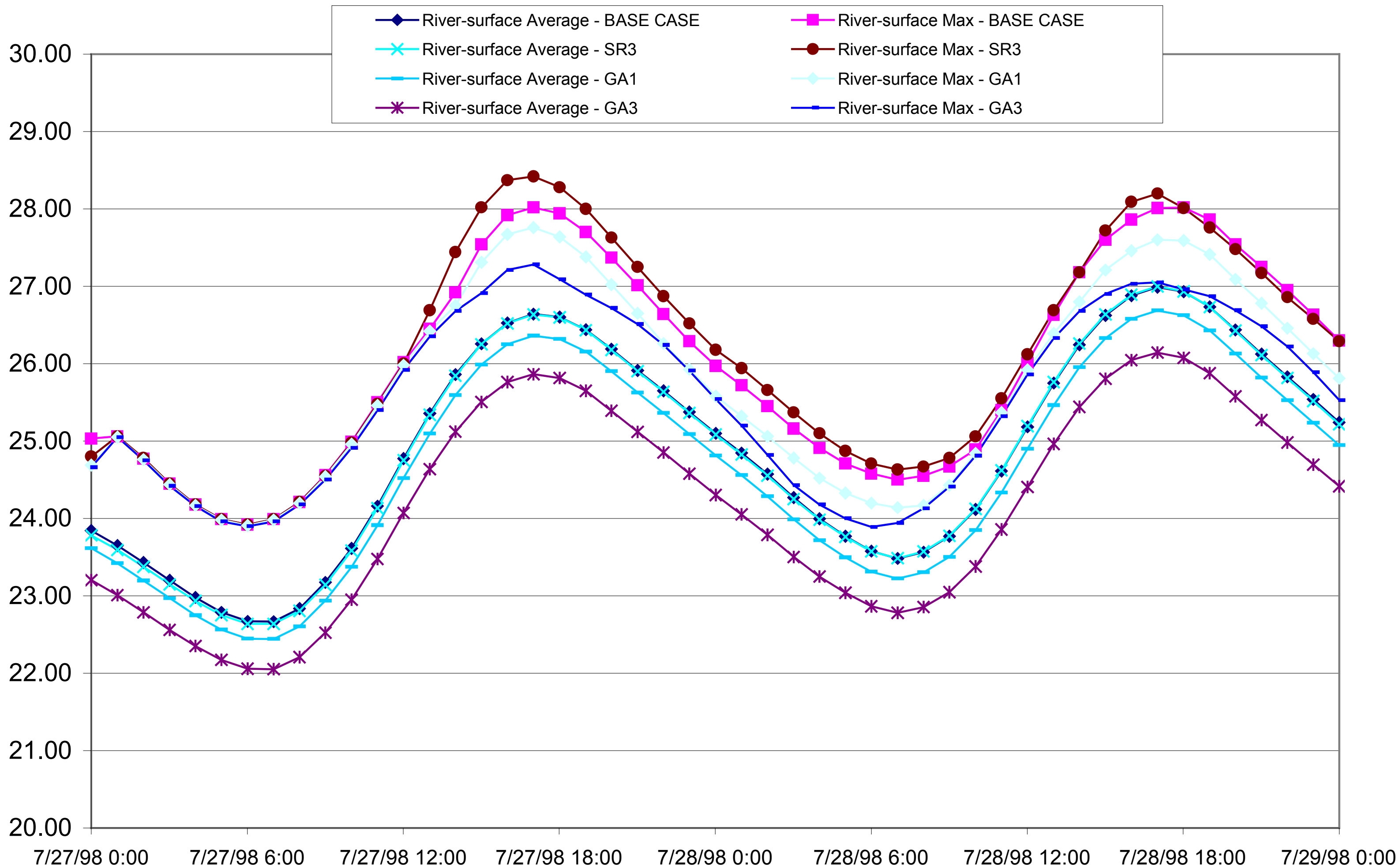
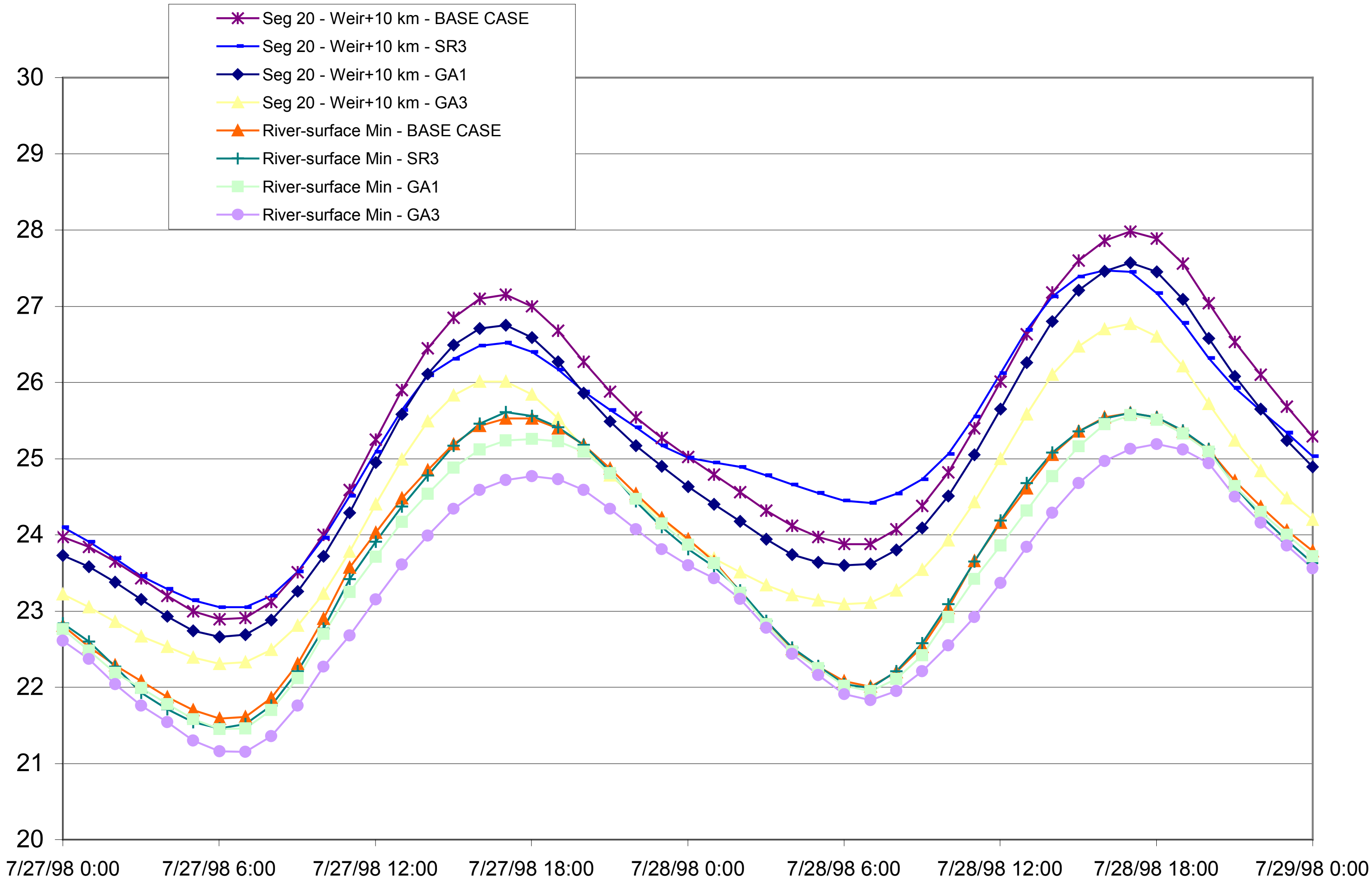


Figure 7-28 Comparison of Scenarios – hourly plot of segment 20 and minimum temperatures



8. Appendix B - Comments on the Draft Report and Author's Responses

8.1 Introduction

Comments from King County personnel and the Corps of Engineers were forwarded to us in several e-mails. The comments are consolidated below for easy reference and reproduced exactly as received.

Responses appear below each comment. For readability on screen and on black-and-white copies, comments appear in red and are italicized; responses are indented.

8.2 Comments from King County personnel

The following are the combined comments from King County Staff that reviewed the document (David Hartley, Kevin Schock and Deb Lester). Comments from Tom Fox will be sent under separate cover.

> No comments were ever received from Tom Fox.

8.2.1 General Comments

Generally a good job. It looks like both 50% shading and 15 cfs of groundwater restoration could reduce extreme temperatures by up to 2 degrees at NE 145 St (segment 20). Either of these options represents a pretty serious challenge.

> We did not do any simulations with 50% shading under the Scope of Work of this contract. Presumably this comment arose from combining the results of this report with the results of Martz et al., (1999) report.
>
> If a combination of management options is to be considered, it would be a good idea to specifically examine those combinations through scenario simulations.

There are some places where reference to a figure number is required

> The report was reviewed again with this comment in mind, and a few instances of missing references were corrected.

Is it possible to provide a summary description in "non-modeling techno-speak" for us lowly biologist types? I found it hard to understand exactly what the model was looking at.

> The comment was noted and addressed to some extent in the revised report. The precursor modeling report by Martz et al. (1999), on which this work and document is based, may help provide more context. A short summary is also enclosed below.
>
> The model computes temperatures along the Sammamish's length using observed upstream and tributary inflow rates and temperatures, observed Lake Washington elevation, observed Lake Washington temperature profiles at Kenmore, and observed meteorological data. Besides these boundary conditions, the model considers many processes including advection and dispersion, bottom slope and friction, channel shape, surface heat exchange and mixing with tributaries and groundwater.

The periods of time for which the computations were done (summer 1998 and summer 1999) were determined by the availability of observed instream temperatures for comparison to computed instream temperatures. To assure good agreement between observed and computed temperatures, a limited number of model parameters were adjusted.

Once adjusted, the model was used to determine the Sammamish River temperatures at a set of low flow and high temperature conditions (Base Case). Finally the model was used to assess the effect of surface withdrawal restoration and groundwater augmentation options (Scenarios) under conditions otherwise identical to the Base Case.

8.2.2 Specific Comments

8.2.2.1 Summary

"Increased groundwater...clearly decreases maximum and average temperatures...even at the smallest examined value of 5 cfs addition" This seems too strong a statement given that the largest change in maximum temperature (at segment 20) resulting from adding 5 cfs is only 0.4 degrees C and that the 2-day average change over all segments was only 0.3 degrees C. These difference are within the error range of the calibration results. Even with 15 cfs of added groundwater, the corresponding cooling effect is only 1.2 degrees at segment 20 and 0.7 degrees over all segments for the 2-day average.

It is agreed that the predicted temperature changes are small in absolute terms, and the report language was modified accordingly.

However, there are two reasons predicted effects should not be considered uncertain or insignificant.

1. Predictions of temperature differences between simulations tend to be more reliable than predictions of absolute temperatures, therefore it is not correct to use the calibration error as the threshold of significance for the predictions of effect of management alternatives.

2. A previous stream temperature modeling study that included an investigation of effects on native fish populations (Jain et. al., 1998) found that small temperature differences similar to those noted in the Sammamish study made a significant difference in predictions of brown trout growth.

8.2.2.2 Model Set up and Data Sets

Page 9 - 1st Paragraph - Can you elaborate on what you mean by the last sentence in that paragraph ".....showed that the direct effects of this approximation are not important more than 1 km above lake Washington"*? Are you saying that the influence of the lake on overall temperature is apparent for 1 km up river?*

Data at Kenmore were only available after August 17, hence it was necessary to make assume the downstream boundary condition for the simulation period prior to August 17. A first approximation was to assume that the data on August 17 applied through the period prior to August 17. Results from the sensitivity section of the report were cited here, ahead of their discussion in Section 3.10, to suggest that this approximation was not likely to lead to a serious error.

The sensitivity test was for extreme conditions (40 C uniform vertical profile in Lake Washington) and the model showed that temperature effects were limited to 1 km up river. However, we did not run the experiment that the commenter suggests –numerical dyeing the Lake Washington water and determining its concentration in the Sammamish. Such an experiment would need to be run with observed, rather than extreme, Lake Washington temperature profiles.

The sentence referred to by the commenter was not considered essential to the report at this point, and was dropped to avoid confusion.

Model sensitivity to downstream bathymetry and downstream boundary data is still discussed in Section 3.9 and 3.10.

In addition, for the final revisions to the report, the authors also ran additional sensitivity simulations to examine the effect of a less extreme downstream temperature boundary condition. This was reported in the updated Section 3.10.

Finally, since the model grid has a longitudinal spacing of 500 m, it is not correct to infer the upstream extent of the downstream boundary condition effect at any finer resolution than 1 km.

Page 11 - Can you please provide more detail in the text that describes what Figure 2-1 is showing?

The caption to Fig 2-1 was modified and the following text was added to the report:

The resulting grid is visualized in Figure 2-1 as a composite of three orthographic views – looking at the grid from the top, from the side, and looking at the downstream segment alone from the downstream end.

8.2.2.3 Calibration and Sensitivity Simulations

Page 15 - Section 3.1, 1st Paragraph - 2nd Bullet - You refer to "computed-observed"? How can it be both? It seems like it should be one or the other? I am confused.

Computed – Observed referred to the algebraic difference between the two, i.e. a minus sign, not a hyphen. The phrase “computed-observed” was replaced with “model error”.

Page 16 - Equation at end of the page - the coefficients associated with "e" must be the same??

Comment was not clear, but a typo was found where the Greek letters gamma and eta were used to refer to the same quantity. This typo was fixed. Perhaps the confusion resulted from this typo. The equation was also enlarged to show the exponential term more clearly.

8.2.2.4 Management Scenarios

Page 24, 2nd to last paragraph- "Historical distributed inflow..." The words, numbers, units, and reference to Bear Creek in this sentence needs more explanation. What is "historical distributed inflow"? Where was the Bear Creek specified flow (i.e., 1.7 X Bear Creek specified flow) numbers come from?

> The original Scope of Work left as "To Be Determined" several flows and temperatures for the Base Case. A memorandum was issued by the Contractor on July 12, 2000 with some suggestions for defining the Base Case and seeking approval for the same. Following is the relevant extract from this memorandum. The entire 2-page memorandum is also reproduced as Appendix C to this report.

Page 26, 1st paragraph regarding discussion of superfluous scenarios and presentation of corresponding data in the final report- my preference would be to avoid time and effort reporting on these scenarios except in the most general way to explain why they are trivial cases.

> The unanimous (as per other comments) approval of our suggestion of dropping redundant scenarios (GA2, SR1 and SR2) is much appreciated.
>
> As requested, a short explanation of the reasons for dropping these scenarios was retained in the final report.

Page 26 - Section 4.4 - 2nd paragraph - This paragraph is a bit confusing.

> This paragraph was rewritten. The paragraph is not central to the report's conclusions or objectives, but was retained as it addresses two subtle objections that may arise in the mind of some readers.

Page 27. Statement about groundwater's "significant cooling effect that increases in magnitude downstream" seems too strong given how small the temperature change is- see comments above under Summary. In the previous Martz et al report, 50% shading of the river that produced slightly higher cooling than the GA1 scenario in the upper part of the river and these current draft were described as having "a relatively minor effect". 50% shading reduced maximum temps at 145th St (segment 20) by 0.5 degrees C and 100% shading by 1.3 degrees C.

> As with the response to the earlier comment, this language was revised.

The comment about an increased downstream effect is misleading. Shouldn't this say that the effect increases along the reach in which groundwater is added? This seems somewhat obvious and perhaps not worth mentioning. Surely the cooling effect does not increase downstream of the point where groundwater augmentation ceases- if this is what is meant, it needs to be explained better.

> This section was rewritten.

8.2.2.5 Recommendations for Future Work

HYDRAULICS- It would be helpful to briefly discuss hydraulic conditions along the river during the calibration periods and the steady state simulations. In other words to add some information *on average depths, top-widths, velocities, and travel times in the selected reaches along the river.*

The calibration period spanned three months in each year, and encountered highly variable hydraulic conditions. Inflows for the calibration period are shown in Figures 7.1 and 7.8. Average depths, top-widths, and velocities are reported in a readable text output format in the “snapshot” output (*.snp file), which is included for most simulations on the attached CD-ROM. Detailed comparison with HEC-RAS, which is a steady state computation, for all calibration runs, was not considered to be either appropriate or within the Scope of Work.

Steady state simulations were only run once to check approximate concurrence of HEC-RAS and CE-QUAL-W2 water surface elevation profiles. The output for steady state CE-QUAL-W2 simulations (using 5 m^3/s inflow and 5 m downstream elevation, and real meteorological data), was added to the Final Report as “Table 7-2 Snapshot output from Steady State simulations with CE-QUAL-W2.”.

Determination of temperature exceedance probabilities and durations- the proposal to perform long term simulations to better evaluate the benefits of shading, flow restoration and other measures makes sense. The benefits of various management actions should not be judged solely on the basis of unusual, extreme conditions.

Agreed.

Further, if the recommendation for further work in “Section 5.4 Biothermal computations” is accepted, it becomes even more relevant to run long-term simulations. Biological impacts of temperatures typically depend on the organism’s thermal exposure history, and are integrated by organisms over time scales longer than the scales at which extereme temperature scenarios are typically defined from physical considerations.

8.2.3 Ken Johnson’s comments

These comments were received in a separate e-mail, and addressed in a telephone conversation as requested by the commenter. The comment and a follow-up clarification are reproduced below. The report was also clarified as requested.

8.2.3.1 Original comment

I understand that you are collecting comments on the recent Sammamish River Temperature Study (Jain et al, 7/21/00). David Hartley gave me a copy that I have looked over.

Previously, I have been trying to understand the hydraulics of the river, in order to connect it with the adjacent groundwater. As part of this effort, I have been trying to resolve some confusion about the vertical datums that are used for the various studies regarding the river. I think that the recent report further confuses the situation.

My understanding of the approximate water surface elevation of the two lakes (ends of the River) is as follows:
<< OLE Object: Microsoft Excel 5.0 Worksheet >>

I have tried to convert the data that I have to the units / datum which might have been used in the report.

To check these data with those in the report, compare the metric values (bold, above) to the "W2 Grid Surface" line in Figure 2-3 of the report. That line goes from approx 8.1 m at the weir near Lake Sammamish to approx 6.8 m near Lake Washington (a difference of about ***1.3*** *m). This line appears to be the only information we have of the water elevations used in the report analysis. I can't be sure which datum is being used here, but that won't affect the difference between the two lake elevations.*

So, the report analysis uses a gradient of about 1.3 m between the lakes, and my best estimate is about 3.9 m. It would appear that the gradient used for the river is about 1/3 the correct one. There may be some of the water level that is not accounted for (e.g., head loss across the weir) but these should be relatively small.

I am not sure of these data (generally the datum is not given in sources). Also, the bed elevation in the same Figure (and in Figure 2-2) is suspect since I believe the HEC-2 or HEC-RAS datum was originally NGVD.

While this difference, if it is true, would significantly affect the hydraulics of the model, I don't think it would have a major effect on the temperature model. However, I don't know how the hydraulic model could be calibrated if the parameters were this far off.

I would be happy to revise this comment based on a clarification of what was actually used in the study. Please let me know if this is not clear or if I have missed some information. I'll be glad to discuss this question with the Corps or with the contractor.

> As requested, the discussion took place via phone. Follow-up comment from Ken appears next.

8.2.3.2 Ken Johnson's follow-up comment after the telephone conversation

I would like to inform all of you that my question has been resolved about what water surface profile (elevation) was used in the hydraulics component of the temperature model for the Sammamish River.

I talked to George Krallis of J.E. Edinger Assocs., Inc., this morning. He said that the hydraulics model that they started from (HEC-RAS) is based on the NGVD datum throughout. The line in Figure 2-3 that I referred to in my comment is simply the top of the model, and not the water surface or even necessarily parallel to it. He directed me to Figure 3-1 of the Draft report, which shows Lake Washington at 5.0 m (or 16.4 ft if you just convert meters to feet), and that for the actual runs they used a 4.5 m (14.8 ft) water surface in Lake Washington, which I agree is typical for late summer.

Since the hydraulics component basically performs a backwater calculation, they modeled only that portion of the river that has a normal backwater curve. The reach of the river immediately below the weir is very much affected by the flow over the weir, and so they left this portion out of the model. Thus the upstream end of the model was, he thought, some 200 m downstream of the weir, and Figure 3-1 shows a HEC-RAS water surface at this boundary of about 6.5 m (21.3 ft) and a W2-V3 model elevation of about 6.05 m (19.8 ft), either of which is possible for this location. The location of the model boundary is above the inflow of Bear Creek, so this important input is included. The temperature at this upstream boundary was set at the temperature in Lake Sammamish, with no distributed input of groundwater beyond this boundary.

I agree that this is a reasonable model for the river, and that leaving out the reach of the river near the weir should not have a significant impact on the modeling. Most of the groundwater inflow probably comes below this point, as the water level in the river is even lower and therefore more of an influence on groundwater.

Mr Krallis said that they would add text to the Final report that will clarify this issue.

The report was modified accordingly.

8.3 Comments from Corps personnel

8.3.1 Marian Valentine's comments

1. Well-written. I'm quite pleased with report and looking forward to sponsor's comments.

Thank you.

2. Typos in para 2, line 2 of summary: "to better locate"

The above ambiguity was noted and the affected sentences modified.

Martz, et al. (1999) noted some limitations in their model calibration, and recommended that additional data be collected, and that sensor locations be improved. They also recommended that Version 3 of the model, which was then under development, be used for its improved river reach modeling capability.

3. Section 2.2, para 1, line 7: "depends on *not only"*

This was modified as suggested.

What does the last sentence mean? Needs more explanation.

This section was rewritten for clarity.

4. Section 2.3.2, para 1: All of the hourly temps supplied were collected by Corps using Optic Stowaways, with some exception. King County daily max/min temps from Lake Sammamish outlet and Bear Creek were used to create hourlies and to replace missing data.

Report was updated to reflect this comment.

5. Figure 2-1: Add to this page descriptions of these views. Sponsor will want to know. A real map showing trib and sensor locations would be a nice accompaniment. Maybe the one from Martz 1999 could be added. This is written as a stand-alone report, so a vicinity map might help.

We would be happy to include such a diagram, but we have no electronic access to one at this time.

6. Figure 2-2: Identify on this page vertical lines as bridges/piers. I know that it's identified in text, but this will improve readability for sponsor.

Captions were updated.

7. Figure 2-3: Note that grid surface is not equivalent to water surface elevation. This is also a readability issue for those less familiar with model.

Captions and associated text was updated.

8. Section 3.8: Use this sensitivity analysis to comment on the "hypothetical modification" in Martz 1999 concerning reduction in Lake Samm outflow temp via withdrawal from lake's hypolimnion. For now, assume that the colder water is available as was done in Martz 1999.

The “hypothetical modification” referred to involved pumping of 10 cfs of 10 C water into the upstream inflow. The modified flow balance was not provided by Martz et al., 1999, but inspection of Figure 2 on page 18 suggests that inflow temperatures were reduced by somewhere between 3 to 6°C, with the larger drops occurring during warmer periods.

On the other hand, the sensitivity analysis in Section 3.8 was done by reducing the inflow temperature by a uniform 1°C throughout the simulation period. Further, the plot in Figure 3-2 showed temperatures at mid-day of Aug 30, 1999, not the 2-day maxima for two different periods as in the Martz 1999 report. Daily maximum temperatures occur around 6 pm, and at slightly different times for different locations.

Given these differences, the results of the two simulation experiments are not easily comparable or scalable to each other, but appear approximately consistent as to the magnitude of the effect, and its attenuation downstream.

The limited investigation of inflow temperature sensitivity carried out by the authors was not included in the Scope of Work, and was carried out only as part of model calibration and sensitivity investigations. A detailed investigation of inflow management options is a possibility for future study, especially with the model extended into Lake Sammamish.

9. Section 3.9: End section with a more explicit statement, such as "Water temperature upstream of Blythe Park is independent of stratification at the downstream end of the river." (This was just a guess as I'm doing this at home with no other info.)

We assumed that this comment referred to Section 3.10. The section was rewritten and the conclusion emphasized. Additional sensitivity studies were carried out and used to supplement the conclusions.

10. Section 4.2: I would concur that SR2 and SR1 don't need to be run. Steve or Dave, confirm this with sponsor.

As per comments received, GA2, SR2 and SR1 were not included in the final report.

11. Section 5.4: Lake Sammamish has a problem with low dissolved oxygen in the hypolimnion leading to phosphorus loading leading to intense algal blooms and subsequent poor water quality. You might comment on the usefulness of extending the model into Lake Samm and examining possible improvements in DO at the bottom that might occur from withdrawal.

A new paragraph was added to the relevant section in “Recommendations for future work”.

8.3.2 Steve Barton's Comments

Sec 3.1, Para. 3: I would prefer you use the term "bias" rather than "Average Mean Error." Para. 4 explains that AME is a measure of bias, but bias is a more appropriate statistical term.

Report was edited to reflect this preferred terminology. The definition of AME was retained to clarify how bias was computed, and a footnote added describing the change in terminology, so as to be consistent with the older but static documents attached on CD-ROM.

Sec 3.4, Para. 1: Define "generally accepted standards" and/or site appropriate references.

Rounds, et al. provide the following for their CE-QUAL-W2 modeling of the Tualatin River "The simulated water temperatures…match the measured data within 1°C, most of the time, with a maximum discrepancy of about 2°C." (Rounds, et al., 1999, p 48; also see Figure 22, same page).

Rounds, Stewart A., Tamara M. Wood, and Dennis D. Lynch. 1999. Modeling Discharge, Temperature, and Water Quality in the Tualatin River, Oregon. U.S. Geological Survey Water-Supply Paper 2465-B. 121 pages.

Also see the following references:

Risley, John C., Relations of Tualatin River Water Temperatures to Natural and Human-Caused Factors: USGS Water Resources Investigations Report No. 97-4071, 143 pages. (several months of simulation)

Conrads, P.A. and P.A. Smith, 1997, Simulation of Temperature, Nutrients, Biochemical Oxygen in the Cooper and Wando Rivers near Charleston, South Carolina, 1992-95, U.S. Geological Survey Water Resources Investigations Report 97-4151, Columbia, South Carolina 58 pages. Several days of simulation in a estuary).

Jobson, Harvey E., 1985 Simulating Unsteady Transport of Nitrogen, Biochemical Oxygen Demand, and Dissolved Oxygen in the Chattahoochee River Downstream from Atlanta, Georgia: US Geological Survey Water Supply Paper No-2264, 36 pages.

Jobson, Harvey E., and Keefer, Thomas N., 1979, Modeling highly transient flow mass and heat transport in the Chattahoochee River near Atlanta, Georgia: U.S. Geological Survey Professional Paper 1136, 41 p.

Jobson, Harvey E., 1980, Thermal modeling of the flow in the San Diego Aqueduct, California, and its relation to evaporation: U.S. Geological Survey Professional Paper 1122, 24 pages.

Sec 3.7, Para. 1: Change "confirmation" to "validation."

Changed.

re Item 10 above: I relayed this item to the sponsor. The sponsor will have final say on this matter.

Sponsor has confirmed that the redundant scenarios do not need to be reported.

9. Appendix C – Text of the memorandum seeking Base Case and Scenario definitions

<Letter Head Deleted>

Memorandum

To:	David Van Rijn
From:	Rajeev Jain Edward M. Buchak
Subject:	Sammamish River Temperature Study Management Scenarios
Date:	July 12, 2000

We would appreciate your comments on the following unresolved issues regarding base case and scenario simulations. Call me or Rajeev if you need more information before answering any of these questions.

1. Local non-trib inflows are "to be determined" in the scope of work. Shall we use 1.7 times the Little Bear Creek as used in the supplied time series data?

2. Local non-trib inflow temperatures are "to be determined" in the scope of work. What temperatures shall we use for these? The 1998 report used Little Bear Creek temperatures for this inflow.

3. Maximum air temperature of 35 C is consistent with the meteorological data we acquired for July 27-28, 1998. However our met. data shows minimum air temperature to be 17.8 C, rather than the Corps specified value of 19.5 C. Our met data is hourly, and it is possible the 3 hour summary from the LCD sheets was used for the Corps' determination of 19.5 C as the minimum value. Please confirm if our hourly met data with a minimum of 17.8 C can be used for the scenario simulations.

4. For producing hourly simulation results as required, we will assume that the river and tributary temperatures show a sinusoidal diurnal variation between the minimum and maximum that are specified for each inflow source. The maximum will be assumed to occur at 6 PM, and the minimum at 6 AM. Please confirm if this interpretation of the maximum and minimum temperature is acceptable.

5. Please confirm that groundwater augmentation applies all along the river, not just in the sections between BC and I-405 crossing, as is stipulated for surface withdrawals. CE-QUAL-

W2 requires distributed inflows to be distributed along the entire waterbody, and will require recoding to apply to a portion of the river.

6. Lake Washington elevation and temperature profile for the base case is “to be determined” in the scope of work. Should we use the values for July 27-28 from 1998 data records?

7. Model simulations show that the effect of initial conditions persists for about 3-4 days. Accordingly, we would like to spin-up the model starting from about 1-2 weeks prior to the July 27-28 base case conditions. Since the initial conditions are not specified in the scope of work, our plan is to run the model with the observed 1998 flow and temperature dataset until July 27 midnight, then run the base case and scenario conditions for July 27 and July 28, and report the hourly results for these two days. Please confirm if these simulations capture the intent of the scenarios.